

Topsoil carbon, nutrients, and water content along an agroforestry chronosequence in a coastal–Caatinga biome transition zone

Adão Barros Moreira de Carvalho

Universidade Federal do Ceará

Everton Alves Rodrigues Pinheiro

Universidade Federal do Ceará

Carlos Alberto Kenji Taniguchi

Brazilian Agricultural Research Corporation

Maria Ivanilda de Aguiar

University for International Integration of the Afro-Brazilian Lusophony

Nazaré Suziane Soares

Universidade Federal do Ceará

Carlos Alexandre Gomes Costa

`alexandre.dena@ufc.br`

Universidade Federal do Ceará

Research Article

Keywords: Soil quality. Climate Emergency. Resilience. Semiarid

Posted Date: September 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10833887/v1>

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

[Read Full License](#)

Additional Declarations: No competing interests reported.

Topsoil carbon, nutrients, and water content along an agroforestry chronosequence in a coastal–Caatinga biome transition zone

Adão Barros Moreira de Carvalho¹; Everton Alves Rodrigues Pinheiro²; Carlos Alberto Kenji Taniguchi³; Maria Ivanilda de Aguiar⁴; Nazaré Suziane Soares¹; Carlos Alexandre Gomes Costa^{*1}

Abstract: Agricultural production is closely related to the natural environment and can cause impact when managed inadequately. Agroforestry systems (AFSs), on the other hand, constitute a sustainable alternative, which can reconcile the production with soil conservation and the ecosystem maintenance. This study aimed to evaluate soil quality aspects in a chronosequence of AFs and compare it with soil under native vegetation (NV) and under monoculture (MONO). Five AFSs were evaluated: AFS0, AFS1, AFS2, AFS3, and AFS4, with zero, one, two, three, and four years of implementation, respectively. The present investigation was conducted in a coastal–Caatinga biome transition zone in the semi-arid region, Brazil, between August 2020 and July 2021. Disturbed soil samples were collected at depths of 0-5 cm and 5-10 cm, with five replicates, in order to determine the following soil quality indicators: total organic carbon (TOC) and its fractions particulate organic carbon (POC) and mineral-associated organic carbon (MAOC); pH, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), and sodium (Na) content, cation exchange capacity (CEC), and base saturation (V%). Moisture and temperature indicators were obtained from the soil profile until a depth of 60 cm and also evaluated. All data gathered were subjected to analysis of variance (ANOVA) and mean comparison tests (Scott-Knott; $p \leq 0.05$). Soil management in the examined AFSs contributed to increased TOC, OC_p, and OC_{am}, in addition to maintaining thermal balance and soil moisture. Those agroforestry systems with a more intensive initial tillage showed greater availability of phosphorus (P) and basic nutrients.

Keywords: Soil quality. Climate Emergency. Resilience. Semiarid

Introduction

Multiple environmental crises are evident in contemporary times, and the trend points towards a substantial global climate imbalance, which is mainly the result of human activities, such as conventional agriculture (Grêt-Regamey et al. 2017; IPCC 2014, 2021; Sharma et al. 2016). It is estimated that 15% to 25% of global carbon dioxide (CO₂) emissions into the atmosphere are caused by agriculture (Foster and Neufeldt 2014), mostly due to the transformation of forests into crops and pastures. Approximately 80% of the world's arable land is used for the production of agricultural commodities (FAO et al. 2021) or other land uses that do not replenish organic matter and consequently impoverish the soil (Demessie et al. 2013). This explains why there is a growing need to propose management alternatives which reduce the negative impacts of agricultural activity on agroecosystems.

In this sense Agroforestry Systems (AFSs), defined as forms of land use in which trees, shrubs, and annual crops are deliberately managed, stand out as an alternative to conventional monoculture systems (Altieri et al. 2017; Zhang et al. 2016). They enhance interactions between tree, shrub, and

¹ Postgraduate Program in Agricultural Engineering (PPGEA) at the Federal University of Ceará (UFC), ² Department of Soil Science (DCS) at the UFC, ³ Brazilian Agricultural Research Company (EMBRAPA), ⁴ University of International Integration of Afro-Brazilian Lusophony (UNILAB); * corresponding author email: alexandre.dena@ufc.br

herbaceous species (Ordóñez et al. 2014), and this increases soil organic matter and has an effect on carbon (C) and nitrogen (N) levels. That's why AFSs represent an option to boost carbon sequestration in agricultural areas (Tonucci et al. 2023), provide greater crop resilience (Foster and Neufeldt 2014), and contribute to mitigation and adaptation to climate change (Andrade et al. 2020).

Agroforestry systems (AFSs) are also strategic to preserve the environment and maintain ecosystem services (Taugourdeau et al. 2014), especially to sustain or even improve functional soil quality (Froufe et al., 2020). Studies on environmental services in AFSs mention benefits for food production, microclimate, nutrient cycling, resistance to pest attacks, soil fertility levels, and water flow regulation (Kuyah et al. 2016). In addition, the environmental benefits of AFSs can generate resources for family farmers, raise agricultural productivity, and reduce inequalities in rural areas (Foster and Neufeldt, 2014); AFSs are considered essential in the transition process from conventional to sustainable agriculture (Thomazini et al. 2015).

A moderate tree cover is not only able to sequester carbon, it also amplifies the groundwater recharge capacity (creation of biopores), and conserves soil moisture (Bargués Tobella et al. 2017; Ilstedt et al. 2016). Bayala and Prieto (2019) demonstrated that, in agroforestry systems, tree plants with deep roots redistribute water to the surface layers of the soil (Pinheiro et al. 2013; Costa et al., 2016); this constitutes an ecological mechanism which makes it possible to produce food in semi-arid climates. Araújo Filho (2013) also observed that AFSs integrated with livestock farming expand the carrying capacity of pastures and ensure physical soil protection against compaction.

Shade trees in agroforestry systems provide resources for soil macrofauna, influence the soil through bioturbation and promote aggregate stability due to the accumulation of organic matter from plant residues (Bardgett et al. 2014; Bottinelli et al. 2015; Chen et al. 2017; Suárez et al. 2021). Soils with a large amount of organic matter typically exhibit low density and high porosity, and this, in turn, combines positively with soil water content (Carvalho et al. 2004; Upson et al. 2016).

Total organic carbon (TOC) is considered an important parameter that influences the main soil functions, as well as soil attributes, like fertility, water flows, and aggregate stability (Suárez et al. 2021). Therefore it is fundamental to evaluate TOC stocks, compartments, and stability, so as to understand their dynamics and plan adequate strategies to maintain a soil quality that attenuates global warming (Lourenço et al. 2019). TOC is also a useful indicator to monitor how adopted management practices are impacting soil quality. Yet, in recently established AFSs, TOC may not be sufficient to detect management changes, and this makes it necessary to evaluate its fractions too, i.e., particulate organic carbon and mineral-associated organic carbon, which are related to the physical protection of aggregates and are more sensitive to management (Conceição et al. 2005; Loss et al., 2009).

Given the large amount of organic matter in agroforestry systems (AFSs), it was expected that the increases would be noticeable from the first years of system implementation. Studies such as those

76 by Cezar et al (2015) and Froufe et al (2020) confirmed this expectation by exposing that AFSs, since
77 the fifth year of implementation, provide stocks of C and soil nutrients, such as nitrogen (N),
78 phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) equivalent to those of well-
79 preserved forests.

80 The hypothesis of this study was that AFS management would elevate the organic carbon
81 content of the soil and nutrient levels, in addition to contributing positively to the soil's water and
82 thermal regime. Therefore, the aim of this study was to evaluate carbon content, fertility of the surface
83 layer, and variations in soil moisture and temperature under agroforestry systems in different years
84 of implementation.

85

86 **Material and methods**

87 The present investigation was conducted in the municipality of Cascavel, metropolitan area of
88 Fortaleza, state of Ceará, Brazil (Fig. 1). According to the Köppen classification the region's climate
89 is tropical humid type Aw, with irregular rainfall and a moderate to low water deficit Average annual
90 rainfall between 1991 and 2021 was 1225 mm, calculated from data provided by the rain gauge station
91 of the Ceará Foundation for Meteorology (FUNCEME) in the municipality; potential
92 evapotranspiration (ET0) was 1603 mm/year.

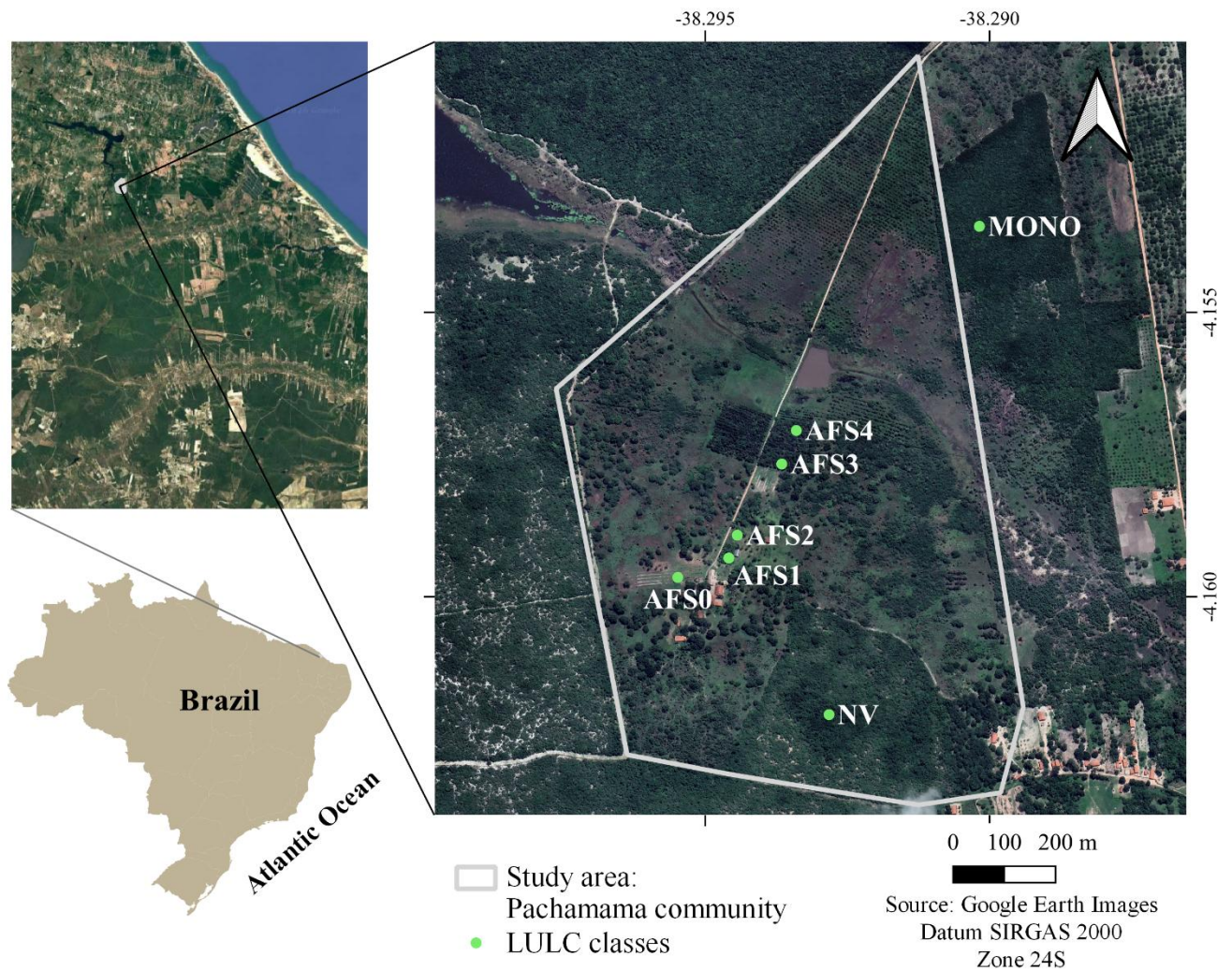


Fig. 1 Location of the study area and indication of different land uses: monoculture (MONO), native Caatinga vegetation (NV) and chronosequence of agroforestry systems implemented in the same year (AFS0), and set up one, two, three and four years earlier (AFS1, AFS2, AFS3, AFS4, respectively).

Land uses land cover (LULC) classes in the study area correspond to native vegetation (NV), agroforestry systems (AFS0, AFS1, AFS2, AFS3 and AFS4) and bean monoculture (MONO) (Fig. 2). The main management practices adopted and general information about essential characteristics are described in Table 1.

Table 1 Description and characterization of land uses in the studied areas in Cascavel, Ceará, Brazil.

Land uses land cover	Acronym	Characteristics and management
Native vegetation	NV	Private ecological reserve, which has been closed to human use for at least 30 years.
Bean monoculture	MONO	Land used for bean planting with the following sequence of management operations: vegetation clearing, then burning followed by stump removal. Soil preparation with harrows, and

		weeding with animal-drawn implements. Dryland cultivation, without use of any soil amendments or fertilizers.
	AFS0	Area planted in 2021 under rainfed conditions, with rows of native trees (<i>Tabebuia sp.</i> , <i>Myracrodruon urundeuva</i> and <i>Swietenia macrophylla</i>) and fruit trees (<i>Anacardium occidentale</i> and <i>Mangifera indica</i>) 6 m apart from each other. In the space between the rows grow exotic and regenerating grasses, which are mechanically mowed.
Agroforestry Systems	AFS1 and AFS2	Areas planted in 2020 and 2019. Cultivation of native trees (<i>T. sp.</i> , <i>M. urundeuva</i> , <i>Erythrina sp.</i> , <i>Hymenaea sp.</i>) and fruit trees (<i>Musa sp.</i> , <i>Citrus spp.</i> , <i>Carica papaya</i> , <i>Morus sp.</i> , <i>Malpighia glabra</i> , <i>A. occidentale</i> , <i>Artocarpus integrifolia</i> , <i>Cajanus cajan</i> , <i>Punica granatum</i> , <i>Annona muricata</i> and <i>M. indica</i>) with 4 m spacing between rows. Cultivation of vegetables, manioc, corn and beans in the inter-rows.
	ASF3 and ASF4	Areas planted in 2018 and 2017. Cultivation of <i>Eucalyptus</i> and <i>Acacia mangium</i> , with 5 m spacing between tree rows; intercropping with banana, cassava, pigeon pea and native trees (<i>T. sp.</i> , <i>M. urundeuva</i>). The inter-rows are mowed mechanically.



Fig. 2 Soil profile of the study area (A) and respective land uses: monoculture (MONO; B), and chronosequence of agroforestry systems implemented in the same year (ASF0; C), and implemented one, two, three and four years before, being ASF1(D), ASF2 (E), ASF3 (F), ASF4 (G), as well as native vegetation (NV; H).

109 In order to determine C and nutrient levels, disturbed soil samples were collected at depths of
110 0-5 cm and 5–10 cm, with five replicates for all the land-use types (native vegetation, monoculture,
111 and agroforestry systems). This sample collection took place in May 2021. After collection, these
112 samples were placed in hermetically sealed plastic bags and sent to the soil laboratory at Embrapa
113 Tropical Agroindustry. There the chemical elements phosphorus (P), potassium (K), calcium (Ca),
114 and magnesium (Mg) were analyzed according to the methodologies described by Silva et al. (2009).
115 The physical fractionation of organic matter into particulate organic carbon (POC) and mineral-
116 associated organic carbon (MAOC) was carried out following Cambardella and Elliott (1992). A
117 portable Umwelt-Geräte-Technik GmbH sensor (model COMBI 6000) was employed to assess
118 moisture content and temperature within the soil profile down to a depth of 60 cm, and the soil profile
119 was stratified in the root zone (Costa et al., 2013; Pinheiro et al., 2013; Costa et al., 2016) as follows:
120 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–40 cm, and 40–60 cm. At each of these depths moisture
121 and temperature readings were taken, always with five replicates across the seven treatments.

122 The data we had obtained with all these proceedings were then statistically analyzed with
123 AgroEstat software. First, data normality was assessed, and since our data did not fit a normal
124 distribution (Monte Carlo) and exhibited high variability, a ($\sqrt{x+1}$) transformation was applied to all
125 parameters. Next, we subjected the transformed data to tests for homogeneity of error variances and,
126 subsequently, examined these results by using an analysis of variance (ANOVA) with F-test. Mean
127 values were then compared with a Scott-Knott test at a 5% probability level

128

129 **Results and discussion**

130

131 **Total organic carbon (TOC), particulate (POC), and mineral-associated (MAOC) carbon**

132 After two years, the management of agroforestry systems (AFSs) resulted in an increase in total
133 organic carbon (TOC) compared to NV and MONO (Fig. 3A). Only in the system managed for just
134 one year (AFS1), TOC values were similar to those of MONO and AFS0 (first cropping cycle).

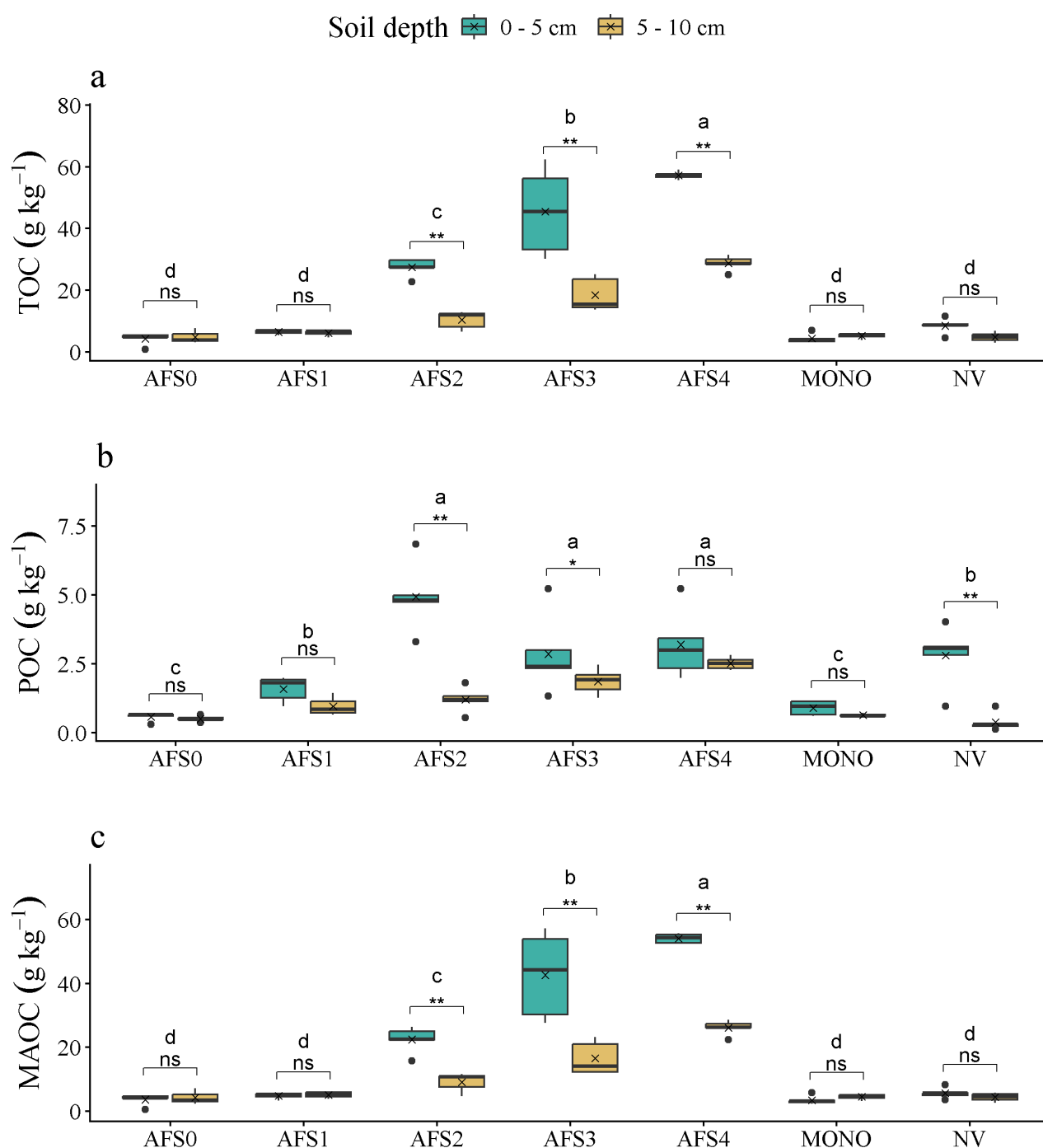


Fig. 3 Total organic carbon (TOC; A), particulate organic carbon (POC; B), and mineral-associated organic carbon (MAOC; C) under monoculture (MONO), native vegetation (NV), and a chronosequence of agroforestry systems established in the same year (AFS0) and one, two, three, and four years before (AFS1, AFS2, AFS3, and AFS4, respectively), at depths of 0–5 cm and 5–10 cm.

These results highlight the potential of agroforestry systems (AFSs) to incorporate organic matter into the soil since their second year of establishment already. This can be attributed to specific management practices during implementation and to intrinsic AFS characteristics, such as soil cover, pruning management, and the diversity and density of herbaceous and tree species. Other studies have

also described that areas under AFSs can reach soil organic carbon (SOC) levels similar to those found in areas under native vegetation at various successional stages (Cardozo et al., 2022). This phenomenon is due to above-ground carbon production, as the vegetation structure of AFSs resembles that of secondary native vegetation of the same age (Cardozo et al., 2022); what also contributes is the fact that plant diversity and density are key factors which drive carbon fixation and the subsequent input of carbon into the soil (Henry et al., 2009). And there are, furthermore, certain pruning practices in AFSs that promote carbon input to the soil (Froufe et al., 2020; Suárez et al., 2021).

For the uppermost soil layer (0 to 5 cm) the relationship between particulate organic carbon (POC) content and time since the creation of the agroforestry systems (AFS) was non-linear (Fig. 3B). Thus, at this depth, the lowest POC values were provided by MONO and AFS0 land-use systems. AFS2, on the other hand, exhibited the highest POC content, followed by AFS3 and AFS4, which yielded similar POC levels, while AFS1 displayed a value similar to that of native vegetation (NV) and higher than those of AFS0 and MONO (Fig. 3B). These results reflect the influence of the different management practices adopted during the establishment and maintenance of the treatments we studied in the present work. Following the approach used in studies conducted in other biomes (Cezar et al. 2015; Froufe et al. 2020), we considered particulate organic carbon (POC) content of the NV to be the baseline for the local ecosystem: It is characterized by *tabuleiro* forest or *carrasco* vegetation in a secondary succession stage of approximately 30 years. The POC content in the MONO system was approximately three times lower than in the NV system: This can be attributed to a reduction of organic matter caused by the use of fire, by soil tillage, and also exposure to prolonged periods of direct sunlight—which accelerates organic matter degradation—as well as the lack of organic matter inputs, given that in MONO area crop residues are utilized for livestock grazing after the harvest.

Particulate organic carbon (POC) values in AFS2 exceeded native vegetation (NV) values by approximately 57%; these higher levels probably resulted from more diverse planting practices and an elevated pruning intensity in this area. POC values were lower in the older agroforestry systems AFS3 and AFS4 than in AFS2; tree density was also lower there. Species composition may influence a systems' capacity to generate POC, just as differences in the composition of intercropped species affect biomass production and C input to the soil (Coulibaly et al. 2017). Similar to what was observed regarding total organic carbon (TOC), POC levels in older systems (with the exception of AFS4) and in native vegetation were higher in the surface soil layer, which contains the majority of organic matter undergoing transformation and offers more favorable conditions to organisms that fragment organic matter (such as ants) and to those that decompose soil organic matter (such as fungi). Loss et al. (2009) had already noticed that POC was more effective at revealing differences between

179 management systems in the uppermost soil layers, and this pattern could be observed from AFS1
180 onwards.

181 We noted that the increase in particulate organic carbon (POC) content occurred linearly with
182 respect to the time since establishment at a depth of 5 to 10 cm, so MONO, NV, and AFS0 exhibited
183 the lowest POC levels: 0.96 g kg⁻¹, 0.38 g kg⁻¹, and 0.50 g kg⁻¹, respectively. Yet, starting from the
184 second year of establishing the agroforestry systems (AFSs), a trend toward stabilizing POC content
185 emerged in this layer, ranging from 1.20 g kg⁻¹ in AFS2 to 2.52 g kg⁻¹ in AFS4. It reflected the lesser
186 influence of pruning practices on this specific layer within the AFSs. A higher POC content in the
187 AFSs primarily revealed the constant input of residues from pruning—a phenomenon widely
188 described in literature, which also indicates that this practice accelerates the cycling process (Bayala
189 et al. 2014; Sharma et al. 2016; Taugourdeau et al. 2014). Time since establishment is also likely to
190 account for the greater increase witnessed in deeper layers, thereby representing a long-term
191 contribution to soil carbon input.

192 As with TOC, two groups of values emerged for mineral-associated organic carbon (MAOC)
193 (Fig. 3C): The first group consisted of MONO, NV, AFS0, and AFS1, which showed similar values
194 cross the two studied layers. A second group comprised AFS2, AFS3, and AFS4; they differed from
195 the others and also from each other, and exhibited MAOC levels that were 341%, 344%, and 448%
196 higher, respectively, than the NV reference. MAOC is the most resilient fraction of organic matter, it
197 is less influenced by management and chemically highly stable, and represents an advanced stage of
198 humification (Loss et al. 2009; Wolschick et al. 2018). The results of the present study demonstrated
199 that the agroforestry system (AFS) management was able to increase MAOC levels in both layers (0–
200 5 cm and 5–10 cm) starting two years after establishment (AFS2). Also from the second year of
201 implementation onwards, MAOC levels differed between the evaluated layers. This probably
202 occurred due to the input of plant biomass from pruning, including tree parts containing complex
203 protein chains and recalcitrant substances, such as trunks and larger-diameter branches. Regarding
204 the influence of plants—especially trees—on MAOC levels, Chiti et al. (2018) conducted a study in
205 Gabon using $\delta^{13}\text{C}$ and $\delta^{14}\text{C}$ isotopes to determine the influence of forest and savanna vegetation on
206 soil TOC formation. They found that, at depths of up to 30 cm, forest vegetation can account for up
207 to 25% of soil TOC, and that trees provide recalcitrant carbon derived from structural components
208 such as waxes, suberin, cutin, and terpenoids.

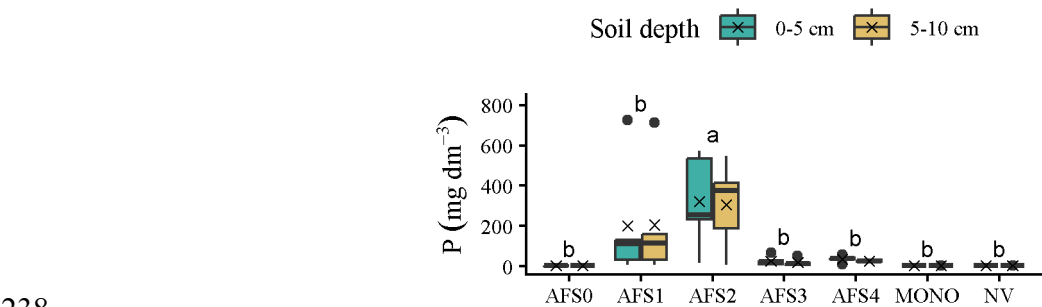
209 In the coastal-Caatinga biome transition zone, soil organic matter and total organic carbon
210 contents are naturally low. Under cashew monoculture, organic matter contents of approximately 13
211 g kg⁻¹ have been reported in the surface soil layers, decreasing to 3–10 g kg⁻¹ in subsurface layers
212 (LIMA et al., 2004). Similarly, a long-term experiment with cashew cultivation showed that, after
213 five years, soil organic matter content was lower under harrowing (8.4 g kg⁻¹) than under manual

weeding (10.7 g kg^{-1}), highlighting the influence of management practices on soil carbon conservation (Ribeiro et al., 2007). Agroforestry systems may provide an alternative pathway for enhancing soil carbon storage and associated ecosystem functions. In these systems, a substantial proportion of soil carbon is stored in mineral-associated fractions, where it is stabilized through organo-mineral interactions and is relatively resistant to management effects (Conceição et al., 2005). Tree-derived carbon can contribute to these stable pools over long periods and at greater soil depths (Chiti et al., 2018). Trees also enhance nutrient cycling through the gradual decomposition and mineralization of litter, with reported half-lives ranging from 15 to 257 days (Froufe et al., 2020), while deep and dimorphic root systems can promote hydraulic redistribution, transferring water from deeper to shallower soil layers and thereby alleviating seasonal water deficits (Bayala; Prieto, 2019). These processes are particularly relevant to family farming in soils where cation exchange capacity is strongly dependent on soil organic matter. Under such conditions, increasing and maintaining soil organic carbon represents a viable and sustainable strategy for improving soil fertility while simultaneously enhancing climate change adaptation and mitigation (Mbow et al., 2014; Altieri et al., 2015).

229

230 Available phosphorus (P)

P levels were higher in AFS2 than in the other land-use systems and also above the average typically found in the soils of that region (Fig. 4). Soil P levels across the different land-use systems reflect the influence of the initial management during system establishment. In a study conducted in the Atlantic Forest biome, Froufe et al. (2020) concluded that agroforestry systems (AFSs) facilitate a synchrony between decomposition and nutrient availability through litter decomposition, and potentially supply at least 5 kg ha^{-1} of P. Our results demonstrated that available P levels in the AFSs remained high or very high, and this was achieved by using pruning residues to maintain soil cover.



238

239 **Fig. 4** Available P levels in monoculture (MONO), native vegetation (NV), and a chronosequence
240 of agroforestry systems (AFSs) at depths of 0–5 cm and 5–10 cm.

241

242

243 **Interchangeable bases**

244 The highest levels of calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and base
245 saturation (V%) were observed in AFS2, whereas the other systems displayed similar values for
246 calcium, magnesium, and potassium. AFS1, AFS3, and AFS4 exhibited intermediate sodium values,
247 which may be attributed to the partial use of irrigation (Fig. 5). Cation exchange capacity (CEC) was
248 highest in AFS4, followed by AFS2 and AFS3. Base saturation (V%) was highest in AFS1 and AFS2,
249 followed by AFS0, MONO, and NV; it was lowest in AFS3 and AFS4 (Fig. 5F). The higher levels
250 of Ca, Mg, and K bases in AFS1 and AFS2 may have resulted from the following two main factors:
251 the application of limestone at planting and a high management intensity during the initial years of
252 establishment. Froufe et al. (2020) had already observed that agroforestry systems (AFSs) contribute
253 significant amounts of the above-mentioned nutrients within the first five years of their establishment,
254 primarily due to the rapid decomposition of leaves and branches, which constitute the bulk of pruned
255 material during this period. Soil CEC is directly influenced by organic matter; AFS3 and AFS4
256 (which were established earlier) exposed the most significant results for this feature, and this indicated
257 a trend toward increasing the pool of nutrients which was available for plant uptake. We hereby
258 demonstrated that AFS management is inherently beneficial for organic matter accumulation,
259 regardless of initial management practices that may involve the addition of extra material at the time
260 of establishment.

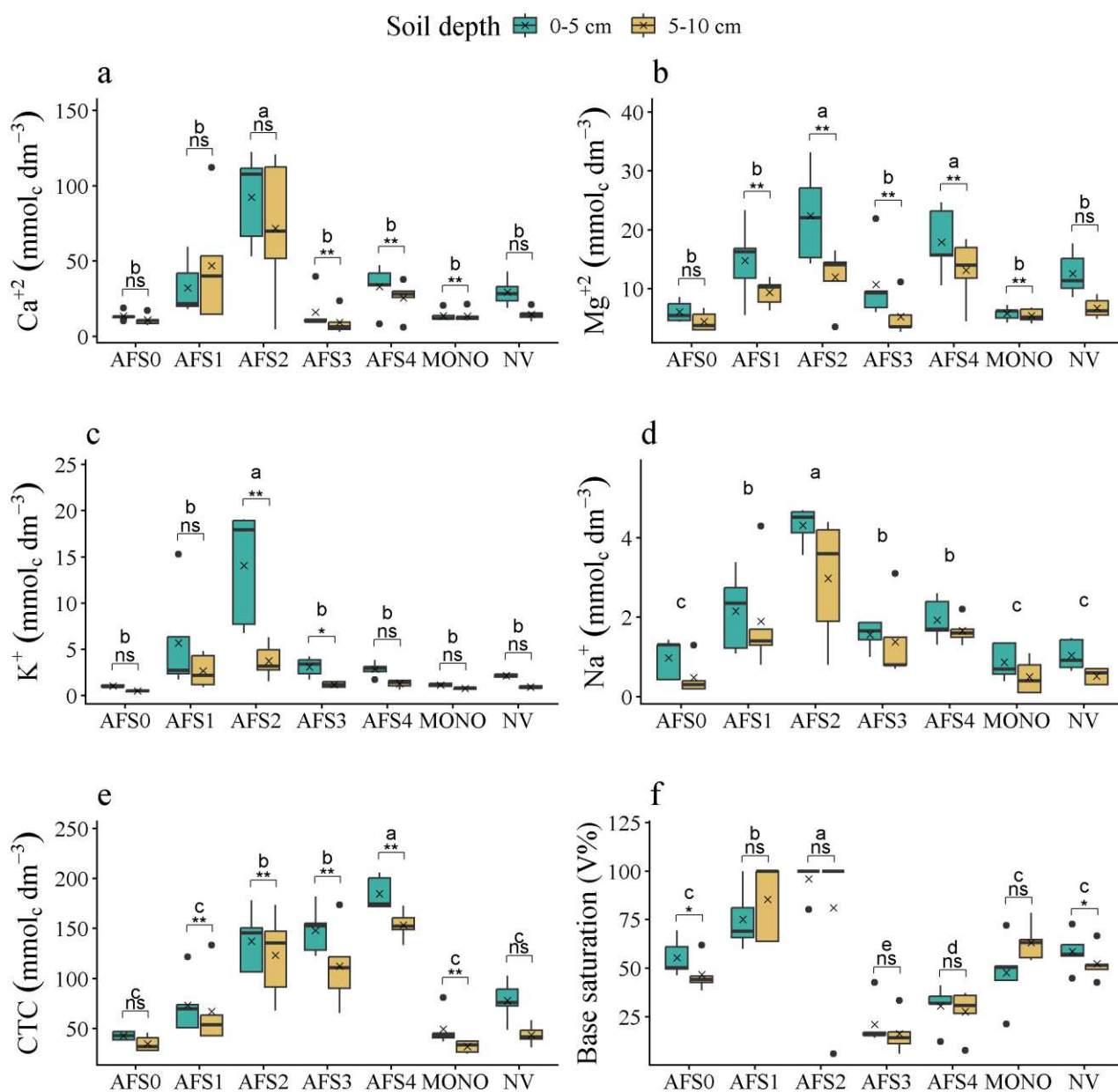


Fig. 5 Levels of calcium (A), magnesium (B), potassium (C), cation exchange capacity (E), and base saturation (F) in monoculture (MONO), native vegetation (NV), and an agroforestry system (AFS) chronosequence, at depths of 0–5 cm (dashed line) and 5–10 cm (solid line).

Elements related to soil acidity

Results regarding soil acidity, pH, and ($\text{H} + \text{Al}$), as well as aluminum saturation (m), reveal that the soils under AFS3 and AFS4 are slightly acidic, whereas all the other land uses fall within safe range for these parameters (Fig. 6).

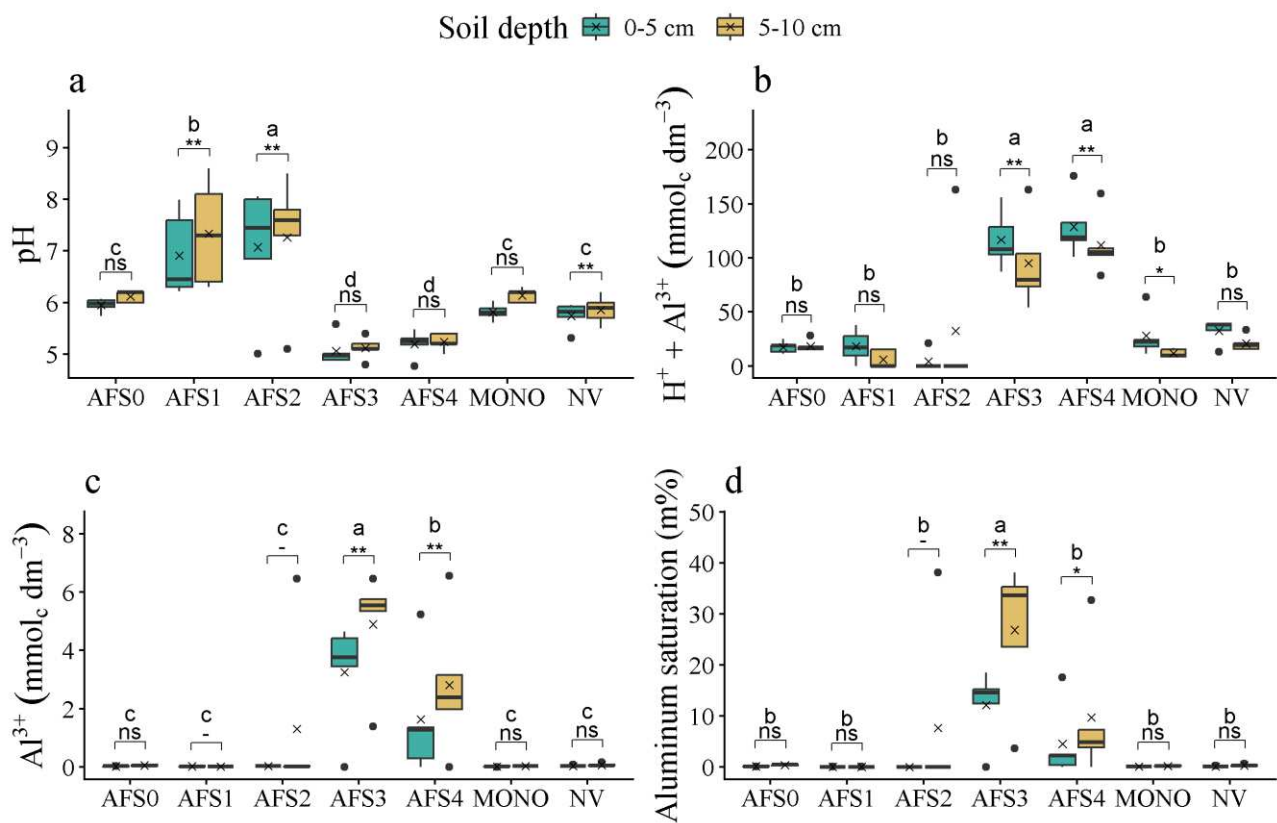


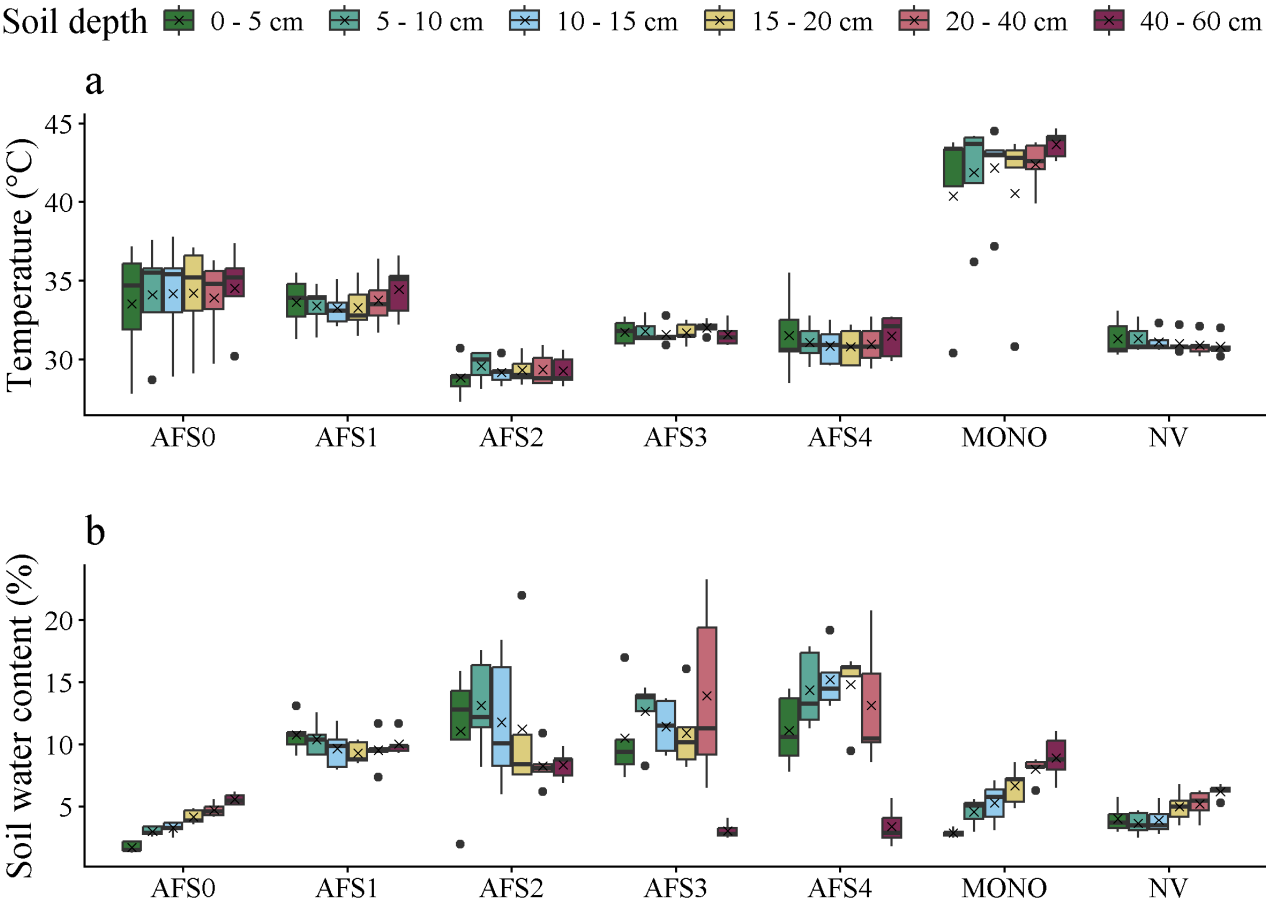
Fig. 6 pH (A), potential acidity (B), aluminum (C), and aluminum saturation (D) in monoculture (Mono), native vegetation (NV), and the agroforestry system (AFS) chronosequence, at depths of 0–5 cm and 5–10 cm.

We could observe that AFS3 and AFS4 exhibited levels of exchangeable acidity, potential acidity, and aluminum saturation above the optimal ranges for most plants. This may be related to the type of pruning material that was used; its high C/N ratio probably influenced acidity parameters, given that the soil in that region did not present exchangeable or potential acidity under other land-use systems, such as NV and MONO. Still, caution is required when evaluating this parameter, since the buffering effect of organic matter, in soils with a high content of it, can mitigate potential negative impacts of acidity on crops (Ebeling et al. 2008). In this case, nutrient recycling is also possible through tree pruning: The commercial elements can be harvested while the remainder—especially leaves and branches—is used as soil cover. Theoretically, this should be enough to restore the base balance of the soil, as nutrients are found in higher proportions in leaves, fine branches, and reproductive parts (Cezar et al. 2015; Froufe et al. 2020; Thomazini et al. 2015).

Soil temperature and humidity

With regard to soil temperature, we noted that the monoculture area (MONO) exhibited higher average temperatures, whereas AFS2 showed the lowest temperature among all land-use types. AFS1,

289 AFS3, AFS4, and NV demonstrated similar values. Soil moisture, in contrast, was lower in AFS0,
 290 NV, and MONO, while higher values could be measured in the other land treatments (Fig. 7).
 291



292
 293 **Fig. 7** Soil temperature (A) and average soil moisture (B) under monoculture (MONO), native
 294 vegetation (NV), and an agroforestry system (AFS) chronosequence, at depths of 0–5 cm; 5–10 cm;
 295 10–15 cm; 15–20 cm; 20–40 cm; and 40–60 cm.

296 The MONO treatment produced highest soil temperature values because this land-use practice
 297 does not allow neither for leaf litter, nor for herbaceous plants to cover the soil uniformly.
 298 Consequently, there is greater direct solar radiation on the soil surface. Higher temperatures within
 299 the soil profile can accelerate microbial respiration rates, and this process degrades soil organic
 300 matter. In a comparative study of coffee grown in agroforestry systems (AFS) versus full-sun systems,
 301 Thomazini et al. (2015) noticed that the high temperatures associated with full-sun cultivation
 302 increase soil CO₂ flux; the authors found a linear relationship between CO₂ emissions and soil
 303 temperature, which leads to faster leaf litter decomposition and potentially greater carbon loss—as
 304 well as a higher contribution to global warming—in full-sun systems compared to AFS. The soil
 305 cover provided by leaf litter and tree canopies in AFS engendered temperature values comparable to
 306 those of the natural system (NV). This result indicates that AFS land use holds potential for both
 307 adapting to and even reducing the effects of climate change on thermal soil regimes. Regarding this

308 potential, Mbow et al. (2014) emphasized that the capacity to generate such benefits must be clearly
309 demonstrated and that climate mitigation measures must be implemented alongside improvements in
310 food production, particularly in regions where family farming predominates.

311 Regarding soil water content, we observed that the older agroforestry systems (AFSs)
312 maintained higher water levels, which probably alleviated the water deficit common during part of
313 the year in semi-arid regions. Although AFS1 and AFS2 received sporadic irrigation, they exhibited
314 moisture levels that were similar to those of AFS3 and AFS4, which were not irrigated. This showed
315 us that the protection provided by tree canopies and leaf litter, along with interactions among the
316 different functional groups, compensated for the lack of irrigation in more mature systems. In this
317 regard, Bayala and Prieto (2019) concluded that a hydraulic redistribution of soil water occurs in
318 agroforestry systems, which promotes water sharing between tree species and herbaceous plants, and
319 that this mechanism is ecologically important for food production in semi-arid regions. Using $\delta^{18}\text{O}$
320 isotopes, Bargués-Tobella (2017) found that AFS trees utilized water from deep sources and
321 redistributed it to the surface, and that they thereby benefited neighboring herbaceous species.

322 When we evaluated soil moisture with stratification inside the root zone (Fig. 8), two moisture
323 patterns could be perceived: one similar to MONO, NV, and AFS0—characterized by lower moisture
324 levels and a slight increase starting at a depth of 20 cm—and another one alike AFS1, AFS2, AFS3,
325 and AFS4, which exhibited similar water content in the top 10 cm. Below this depth, a downward
326 trend was observed for AFS1 and AFS2; whereas AFS3 and AFS4 revealed a quite pronounced trend
327 of decreasing moisture starting at depths of 30 cm and 40 cm, respectively. Figure 8 indicates that
328 agroforestry stems are capable of retaining more soil water and that this is directly related to soil
329 organic matter content. These results corroborate those of Thomazini et al. (2015), who found higher
330 water retention in coffee-based agroforestry systems: Their findings suggested that the trees within
331 these systems regulate the available soil water by promoting infiltration thanks to the presence of
332 biopores, and by enhancing the hydraulic lift to upper soil layers (Bargués-Tobella et al. 2017; Bayala
333 and Prieto, 2019; Kuyah et al. 2016)

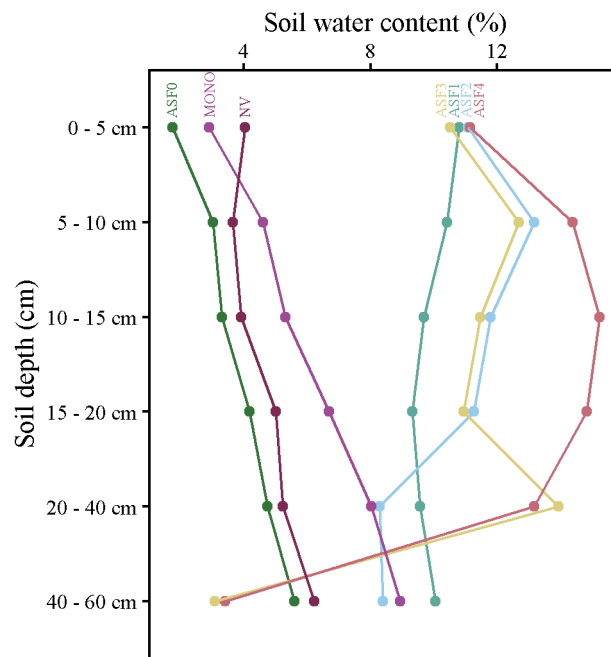


Fig. 8 Soil moisture (%), in a 0–60 cm profile, under monoculture (MONO), native vegetation (NV), and an agroforestry system (AFS) chronosequence.

Conclusions

Agroforestry systems led to an increase in total organic carbon, particulate organic carbon, and mineral-associated organic carbon levels—especially from the second year of establishment onwards. This highlights their potential to improve soil quality.

Those agroforestry systems that were subjected to more intensive initial site preparation reached higher levels of phosphorus and exchangeable bases, which proves that management practices adopted during establishment influence soil nutrient availability.

More established agroforestry systems showed higher soil moisture content and lower soil temperatures compared to monoculture; this way they demonstrated their potential to enhance not only soil moisture management, but also thermal regulation.

Acknowledgments The authors thank to the owners of the Pachamama farm (Dr. Marco Antônio, Ms. Mércia, and Gaia) in the municipality of Cascavel, Ceará.

Author contribution ADMC contributed to the conception of the work, wrote the main manuscript text, conducted the laboratory analyses, prepared the tables and figures, contributed to the acquisition and analysis of data. NSS contributed to the conception of the work, wrote the main manuscript text, prepared the tables and figures. CAGC provided scientific supervision, contributed to the conception of the work, interpreted the results, and critically revised the manuscript, wrote the main manuscript text, contributed to the acquisition and analysis of data. EARP contributed to the conception of the work, wrote the main manuscript text. CAKT wrote the main manuscript text, conducted the laboratory analyses, contributed to the acquisition and analysis of data. MIA wrote the main manuscript text, contributed to the acquisition and analysis of data. All authors contributed

361 to the discussion of the results, contributed to the analysis and interpretation of data, and reviewed
362 the manuscript.
363

364 **Funding** Brazilian National Research Council (CNPq) ConectSAFs/CNPq 420528/2025-3 and
365 CNPq 308660/2025-0, the Chief Scientist Program in Agriculture of the Government of the State of
366 Ceará (SDE/Funcap), the National Institute of Science and Technology in Sustainable Agriculture
367 in the Tropical Semi-Arid Region – INCTAgriS (CNPq/Funcap/Capes). This study was financed in
368 part (Finance Code 001) and the Article Processing Charge (APC) for the publication of this
369 research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil
370 (CAPES)
371

372 **Data availability** The data generated and analyzed in this study are part of the first author's
373 master's thesis, developed within the Graduate Program in Agricultural Engineering at the Federal
374 University of Ceará (PPGEA/UFC). The data are not currently deposited in a public repository but
375 are available from the corresponding.
376

377 **References**

- 378 Altieri MA, Nicholls CI (2017) The adaptation and mitigation potential of traditional agriculture in
379 a changing climate. *Clim. Chang.* 140:33–45. <https://doi.org/10.1007/s10584-013-0909-y>
- 380 Andrade EM, Guerreiro MJS, Palácio HAQ, Campos DS (2020) Ecohydrology in a Brazilian tropical
381 dry forest: thinned vegetation impact on hydrological functions and ecosystem services. *J Hydrol:*
382 *Regional Studies* 27:100649. <https://doi.org/10.1016/j.ejrh.2019.100649>
- 383 Araújo Filho JA (2013) Manejo Pastoril Sustentável da Caatinga. Projeto Dom Helder Câmara, Recife
- 384 Bardgett RD, Mommer L, De Vries FT (2014) Going underground: Root traits as drivers of ecosystem
385 processes. *Trends Ecol Evol* 29:692–699 <http://dx.doi.org/10.1016/j.tree.2014.10.006>
- 386 Bargués Tobella A, Hasselquist NJ, Bazié HR, Nyberg G, Laudon H, Bayala J, Ilstedt U (2017)
387 Strategies trees use to overcome seasonal water limitation in an agroforestry system in semiarid West
388 Africa. *Ecohydrology* 10. <https://doi.org/10.1002/eco.1808> .
- 389 Bayala J, Sanou J, Teklehaimanot Z, Kalinganire A, Ouédraogo SJ (2014) Parklands for buffering
390 climate risk and sustaining agricultural production in the Sahel of West Africa. *Curr Opin Environ*
391 *Sustain* 6:28–34. <https://doi.org/10.1016/j.cosust.2013.10.004>
- 392 Bayala J, Prieto I (2019) Water acquisition, sharing and redistribution by roots: applications to
393 agroforestry systems. *Plant Soil* 453:17–28. <http://dx.doi.org/10.1016/j.cosust.2013.10.004>
- 394 Bottinelli N, Jouquet P, Capowiez Y, Podwojewski P, Grimaldi M, Peng X (2015) Why is the
395 influence of soil macrofauna on soil structure only considered by soil ecologists? *Soil Till Res*
396 146:118–124. <https://doi.org/10.1016/j.still.2014.01.007>
- 397 Cambardella CA, Elliott ET (1992) Particulate soil organic-matter changes across a grassland
398 cultivation sequence. *Soil Sci Soc Am J* 56:777–783.
399 <https://doi.org/10.2136/sssaj1992.03615995005600030017x>
- 400 Carvalho R, Goedert WJ, Armando M.S (2004) Atributos físicos da qualidade de um solo sob sistema
401 agroflorestal. *Pesquisa Agropecuária Brasileira* 39:1153–1155. <https://doi.org/10.1590/s0100-204x2004001100015>
402

403 Cardozo, E. G., Celentano, D., Rousseau, G. X., Silva, H. R. e., Muchavisoy, H. M., & Gehring, C.
 404 (2022). Agroforestry systems recover tree carbon stock faster than natural succession in Eastern
 405 Amazon, Brazil. *Agroforestry Systems*, 96(5–6), 941–956. [https://doi.org/10.1007/s10457-022-](https://doi.org/10.1007/s10457-022-00754-7)
 406 00754-7

407 Cezar RM, Vezzani FM, Schwiderke DK, Gaiad S, Brown GG, Seoane CES, Froufe LCM (2015)
 408 Soil biological properties in multistrata successional agroforestry systems and in natural regeneration.
 409 *Agrofor Syst* 89:1035–1047. <https://doi.org/10.1007/s10457-015-9833-7>

410 Chen C, Liu W, Jiang X, Wu J (2017) Effects of rubber-based agroforestry systems on soil
 411 aggregation and associated soil organic carbon: Implications for land use. *Geoderma* 299:13-24.
 412 <https://doi.org/10.1016/j.geoderma.2017.03.021>

413 Chiti T, Rey A, Jeffery K, Lauteri M, Mihindou V, Malhi Y, Marzaioli F, White LJT, Valentini R
 414 (2018) Contribution and stability of forest-derived soil organic carbon during woody encroachment
 415 in a tropical savanna. A case study in Gabon. *Biol Fertil Soils* 54:897–907.
 416 <https://doi.org/10.1007/s00374-018-1313-6>

417 Conceição PC, Amado TJC, Mielniczuk J, Spagnollo E (2005) Soil organic matter and other attributes
 418 as indicators to evaluate soil quality in conservation systems. *Rev Bras Ciênc Solo* 29:777-788.
 419 <https://doi.org/10.1590/S0100-06832005000500013>

420 Costa, C.A.G., de Araújo, J.C., Lopes, J. W. B., Pinheiro, E.A.R. Permanence of water effectiveness
 421 in the root zone of the caatinga biome. *Revista Caatinga*, v. 29, p. 692-699, 2016.
 422 <https://doi.org/10.1590/1983-21252016v29n320rc>

423 Costa, C.A.G., Lopes, J. W. B., Pinheiro, E.A.R., de ARAÚJO, J.C., gomes Filho, R. R. Spatial
 424 behaviour of soil moisture in the root zone of the Caatinga biome. *Revista Ciência Agronômica*, v.
 425 44, p. 685-694, 2013. <https://doi.org/10.1590/S1806-66902013000400004>

426 Coulibaly JY, Chiputwa B, Nakelse T, Kundhlande G (2017) Adoption of agroforestry and the impact
 427 on household food security among farmers in Malawi. *Agric Syst* 155:52–69.
 428 <https://doi.org/10.1016/j.agsy.2017.03.017>

429 Demessie A, Singh, BR, Lal R (2013) Soil carbon and nitrogen stocks under chronosequence of farm
 430 and traditional agroforestry land uses in Gambo District, Southern Ethiopia. *Nutr Cycl Agroecosyst*
 431 95:365-375. <https://doi.org/10.1007/s10705-013-9570-0>

432 Ebeling AG, Anjos LHC, Perez DV, Pereira MG, Valladares GC (2008) Relação entre acidez e outros
 433 atributos químicos em solos com teores elevados de matéria orgânica. *Bragantia* 67:429-
 434 439. <https://doi.org/10.1590/S0006-87052008000200019>

435 FAO, IFAD, UNICEF, W & W (2021) The State of Food Security and Nutrition in the World 2021.
 436 Rome.

437 Foster K, Neufeldt H (2014) Biocarbon projects in agroforestry: Lessons from the past for future
 438 development. *Current Opinion in Environmental Sustainability* 6:148–154.
 439 <https://doi.org/10.1016/j.cosust.2013.12.002>

440 Froufe LCM, Schwiderke DK, Castilhano AC, Cezar RM, Steenbock W, Seoane CES, Bognola IA,
 441 Vezzani FM (2020) Nutrient cycling from leaf litter in multistrata successional agroforestry systems
 442 and natural regeneration at Brazilian Atlantic Rainforest Biome. *Agrofor syst* 94:159-171.
 443 <https://doi.org/10.1007/s10457-019-00377-589>

444 Grêt-Regamey A, Sirén E, Brunner SH, Weibel B (2027) Review of decision support tools to
 445 operationalize the ecosystem services concept. *Ecosyst Serv* 26:306–315.
 446 <https://doi.org/10.1016/j.ecoser.2016.10.012>

447 Henry M, Tiftonnell P, Manlay RJ, Bernoux M, Albrecht A, Vanlauwe B (2009) Biodiversity, carbon
 448 stocks and sequestration potential in aboveground biomass in smallholder farming systems of western
 449 Kenya. *Agric Ecosyst Environ* 129:238-252. <https://doi.org/10.1016/j.agee.2008.09.006>

450 Ilstedt U, Bargués Tobella A, Bazié HR et al (2016) Intermediate tree cover can maximize
 451 groundwater recharge in the seasonally dry tropics. *Sci Rep* 6:1-12. DOI: 10.1038/srep21930
 452 <https://doi.org/10.1038/srep21930>

453 IPCC (2014) Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment
 454 Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: Cambridge
 455 University Press.

456 IPCC (2021) Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis*.
 457 Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on
 458 Climate Change. Cambridge University Press.

459 Kuyah S, Öborn I, Jonsson M et al (2016) Trees in agricultural landscapes enhance provision of
 460 ecosystem services in Sub-Saharan Africa. *Int J Biodivers Sci Ecosyst Serv Manag* 12:255–273.
 461 <https://www.tandfonline.com/doi/abs/10.1080/21513732.2016.1214178>

462 LIMA, H. V.; SILVA, A. P.; JACOMINE, P. K. T.; ROMERO, R. E.; LIBARDI, P. L. Identification
 463 and characterization of cohesive soils in the State of Ceará, Brazil. *Rev Bras Ciênc Solo*, Viçosa, v.
 464 28, n. 3, p. 467-476, 2004 <https://doi.org/10.1590/S0100-06832004000300008>

465 Loss, A, Pereira MG, Schultz N, Anjos LHC, Silva EMR (2009) Carbono e frações granulométricas
 466 da matéria orgânica do solo sob sistemas de produção orgânica. *Ciência Rural* 39:1067-1072.
 467 <https://doi.org/10.1590/S0103-84782009005000036>

468 Lourenço VR, Costa CAG, Almeida AMM, Pereira FGS, Morais, AB (2019) Temporal stability of
 469 total organic carbon of soils under different uses in the Caatinga biome. *Rev Caatinga* 32:760–768.
 470 <https://doi.org/10.1590/1983-21252019v32n320rc>

471 Mbow C, Smith P, Skole D, Duguma L, Bustamante M (2014) Achieving mitigation and adaptation
 472 to climate change through sustainable agroforestry practices in África. *Current Opinion in*
 473 *Environmental Sustainability* 6:8–14. <https://doi.org/10.1016/j.cosust.2013.09.002>

474 Ordonez JC, Luedeling E, Kindt R, Tata HT, Harja D, Jamnadass R, Noordwijk M van (2014)
 475 Constraints and opportunities for tree diversity management along the forest transition curve to
 476 achieve multifunctional agriculture. *Current Opinion in Environmental Sustainability* 6:54–60.
 477 <https://doi.org/10.1016/j.cosust.2013.10.009>

478 Pinheiro, E.A.R., Costa, C.A.G., de Araújo, J.C. Effective root depth of the Caatinga biome. *Journal*
 479 *of Arid Environments*, v. 89, p. 1-4, 2013. <https://doi.org/10.1016/j.jaridenv.2012.10.003>

480 RIBEIRO, K. A.; OLIVEIRA, T. S.; MENDONÇA, E. S.; XAVIER, F. A. S.; MAIA, S. M. F.;
 481 SOUSA, H. H. F. Soil quality in soil management systems in dwarf cashew crops. *Rev Bras Ciênc*
 482 *Solo*, Viçosa, v. 31, n. 2, p. 341-351, 2007. <https://doi.org/10.1590/S0100-06832007000200016>

483 Sharma R, Chauhan SK, Tripathi AM (2016) Carbon sequestration potential in agroforestry system
 484 in India: an analysis for carbon project. *Agroforest Syst* 90:631–644. <https://doi.org/10.1007/s10457->

485 015-9840-8

486 Silva FC, Abreu MF, Pérez DV et al (2009) *In*: SILVA, F. C. (Ed.). Manual de análises químicas de
487 solos, plantas e fertilizantes. Brasília: 107-189.

488 Suárez LR et al (2021) Cacao agroforestry systems improve soil fertility: Comparison of soil
489 properties between forest, cacao agroforestry systems, and pasture in the Colombian Amazon.
490 *Agricult Ecosyst Environ* 314. <https://doi.org/10.1016/j.agee.2021.107349>

491 Taugourdeau, S. et al (2014) Leaf area index as an indicator of ecosystem services and management
492 practices: An application for coffee agroforestry. *Agricult Ecosyst Environ* 192:19–37.
493 <http://dx.doi.org/10.1016/j.agee.2014.03.042>

494 Thomazini A, et al (2015) SOC dynamics and soil quality index of agroforestry systems in the
495 Atlantic rainforest of Brazil. *Geoderma Reg* 5:15–24. <http://dx.doi.org/10.1016/j.geodrs.2015.02.003>

496 Tonucci EG, Vogado RF, Silva RD, Pompeu ECFF, Oda-Souza M, Souza HA. Agroforestry system
497 improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid
498 region. *Rev Bras Cienc Solo*. 2023;47:e0220124. <https://doi.org/10.36783/18069657rbcs20220124>

499 Upson MA, Burgess, PJ, Morison JIL (2016) Soil carbon changes after establishing woodland and
500 agroforestry trees in a grazed pasture. *Geoderma*, v. 283, p. 10–20, 2016.
501 <http://dx.doi.org/10.1016/j.geoderma.2016.07.002>

502 Wolschick NH et al (2018) Long-Term Effect of Soil Use and Management on Organic Carbon and
503 Aggregate Stability. *Rev Bras Ciênc Solo* 42:170393, 2018.
504 <https://doi.org/10.1590/18069657rbcs20170393>

505 Zhang Y, Xiao Q, Huang M (2016) Temporal stability analysis identifies soil water relations under
506 different land use types in an oasis agroforestry ecosystem. *Geoderma* 271:150–160.
507 <https://doi.org/10.1016/j.geoderma.2016.02.023>

508

509

510 Statements and Declarations

511

512 Competing Interests:

513 Please see the relevant sections in the submission guidelines for further information as well as
514 various examples of wording. Please revise/customize the sample statements according to your own
515 needs.

516

517

518 number of words as follows:

- 519 • Total number of words (including references): 6412
- 520 • Total number of words (excluding references): 5069
- 521 • Abstract number of words: 248
- 522 • Number of words in Supplementary Information: N/A

523