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ORIGINAL ARTICLE

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Soil organic carbon in tropical shade coffee agroforestry following land-use changes in Mozambique

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Abstract

Coffee (*Coffea* L.) agroforestry systems (CAFS) and wooded grasslands (WG) have been pointed out as having high soil organic carbon (SOC) storage potential compared to monoculture systems. Studies analyzing the response of soil bulk density (BD) and SOC to the conversion of WG to slash-and-burn agriculture (SBA) and to CAFS are lacking in southern Africa. This study was conducted in the buffer zone of Gorongosa National Park (Mozambique), where depth profiles of BD and SOC were estimated to 0- to 100-cm soil depth in WG, SBA, and CAFS sites, with coffee shrubs aged 3, 5, and 8 years after planting. The stratification ratio (SR) was used as an indicator of soil quality and recovery from disturbance. BD and SOC stocks varied significantly among land use systems and coffee ages only in the surface soil layer (0–20 cm). SOC stocks of the surface soil and SR increased with increasing coffee age. Compared to SBA, significant increases in SOC stocks were only observed 5 years after implementation of CAFS. WG conversion to SBA did not alter SOC stocks in any soil layer; however, it led to decreased SR. Surface SOC stocks were 25.6 and 33.7 Mg ha^{-1} in WG and SBA, and 28.0, 41.9, and 61.1 Mg ha^{-1} in 3- and 5- and 8-year-old CAFS (mean SOC accumulation of 6.65 Mg ha^{-1} year^{-1}). This study reveals that CAFS have the potential to increase belowground carbon sequestration when compared to SBA and WG over comparable soils, making it a practical option for climate change mitigation.

1 | INTRODUCTION

Globally, agroforestry systems (AFS) are estimated to occupy more than 1.0 billion ha (Nair et al., 2009), and coffee (*Coffea* L.) agroforestry systems (CAFS) are practiced in 10% of this area (Chatterjee et al., 2019; Leff et al., 2004; Noponen et al., 2013). Shade coffee systems consist of coffee shrubs grown under a woody overstorey providing shade, and multiple ecosystem goods and services (i.e., wood and biodiversity conservation; Noponen et al., 2013). CAFS are estimated to constitute 48% of cultivated coffee fields globally and are mainly implemented by smallholder farmers and communities in varied regions (Somarriba & Lopez-Sampson, 2018). Hence, assessing the climate change mitigation potential of CAFS becomes indispensable to stakeholders engaged with ecosystem services payment schemes.

Abbreviations: AFS, agroforestry systems; BD, soil bulk density; CA3, coffee plantation aged 3 years; CA5, coffee plantation aged 5 years; CA8, coffee plantation aged 8 years; CAFS, coffee agroforestry systems; EMS, equivalent soil mass; FD, fixed depth; GNP, Gorongosa National Park; SBA, slash-and-burn agriculture; SOC, soil organic carbon; SR, stratification ratio; WG, wooded grasslands.

CAFS are mainly studied in Central and South America (Dossa et al., 2008; Ehrenbergerová et al., 2016), where the major coffee-producing countries are located, namely, Brazil, Colombia, Mexico, Honduras, Peru, and Guatemala (International Coffee Organization, 2019; Voora et al., 2019), and where AFS have become an important land use (Ehrenbergerová et al., 2016). Similar studies are lacking for southern Africa, where coffee production is emerging (Preuss, 2023), as in Mozambique. African coffee accounted for 11% of the total global coffee bean production in 2023 (International Coffee Organization, 2023), with the top producers coming from Eastern and Western Africa (Preuss, 2023): Ethiopia (39%), Uganda (23%), Ivory Coast (13%), Tanzania (6%), and Kenya (5%), with these countries accounting for roughly 86% of total African output (Preuss, 2023).

In Mozambique, CAFS are mainly promoted by programs aiming at stopping the advances of slash-and-burn agriculture (SBA) and reforesting degraded lands. One successful project was introduced in Canada (near the Morombodzi Falls and Mount Gorongosa), within the buffer zone of the Gorongosa National Park (GNP) in 2013. The "Gorongosa coffee" is cultivated in two ways: (1) managed directly by the GNP, utilizing local labor, and (2) by local farmers with technical support from the GNP and then sold to the park. Coffee plants are grown by families and small communities by intercropping with indigenous trees, either planted or those left in agricultural lands, in former itinerant lands. Thus, coffee is a source of revenue for the local community, whether through wages or sales, and it facilitates reforestation of the original vegetation (Ramires, 2018). In addition, profits arising from the coffee sales are utilized in the maintenance of conservation and human development programs, such as the construction of schools and hospitals (Ramires, 2018).

Shade coffee systems are often associated to reforestation, but may also relate to deforestation (Somarriba & Lopez-Sampson, 2018). The involved land-use changes are reported to impact the soil organic carbon (SOC) stocks (Don et al., 2011; Guo & Gifford, 2002; Hombegowda et al., 2016; Laganière et al., 2010). Enhanced SOC stocks are frequently reported in AFS compared to pastures and monocultural crop fields (Magalhães, 2023; Nair et al., 2009; Noponen et al., 2013; Pardon et al., 2017), either due to the integration of woody perennials in croplands and pastures (agrisilvicultural or silvopastoral systems). Hence, AFS are more sustainable practices than shifting cultivation due to their potential of sequestering atmospheric CO_2 and reverting the SOC exhaustion (FAO, 2001). As an example, SOC stocks in CAFS were 50% higher compared to monocultures down to 1-m soil depth and only 3.4% lower than forests (Chatterjee et al., 2018). However, various authors (Noponen et al., 2013; Upson et al., 2016) argued that it cannot be assumed that AFS necessarily lead to increased SOC stocks, as increasing aboveground carbon stocks (by establishing trees or perennial crops) does not result in an immediate addition in SOC. Noponen et al. (2013) pointed out that SOC stocks might even decrease in CAFS, due to the influence of multiple factors, including site-specific conditions (i.e., terrain and soil type), past land uses and current management practices (Chatterjee et al., 2019).

Core Ideas

- Soil organic carbon (SOC) maintained following wooded grassland (WG) conversion to shifting cultivation.
- SOC increased as coffee agroforestry plantations (CAFS) aged.
- Soil quality declined with WG conversion to slash-and-burn agriculture.
- CAFS improved soil quality as they aged.

Most of the studies on the effects of land-use change on SOC in Mozambique refer to *miombo* conversion to itinerant agriculture (Magalhães, 2023; Magalhães & Mamugy, 2020; Montfort et al., 2021; Ryan et al., 2011; Williams et al., 2008; Woollen et al., 2012). The responses of SOC due to other land-use changes are less understood, as for example, the case of wooded grasslands (WG; pastures), at influence of specific socioeconomic and environmental conditions. Shifting cultivation or SBA, accounts for around 60% of the tropical deforestation (FAO, 2001), and is argued as leading to SOC depletion (Montfort et al., 2021; Walker & Desanker, 2004), which varies according to land use and implemented practices (Magalhães, 2023). Moreover, SBA is the main driver of forest clearance in Mozambique, accounting for 65% of the greenhouse gas emissions due to deforestation (CEAGRE & Winrock International, 2016). SBA is employed in this study as a synonym for shifting cultivation, not as a specific type of shifting cultivation, even though burning weeds and agricultural residues is prohibited in the study region (Gorongosa National Park buffer zone).

The CAFS of Africa's two largest coffee-producing countries, Ethiopia and Uganda (Preuss, 2023), contain SOC stocks comparable to those found in tree-based SBA (Lemma, 2018; Tumwebaze & Byakagaba, 2016). Africa's WG has more varying SOC levels, ranging from 3 to 93 Mg ha^{-1} (Tessema et al., 2020). Research carried out in Mozambique showed that while surface SOC stores in tree-based SBA lands are over 50 Mg ha^{-1} (Magalhães, 2023; Magalhães & Mamugy, 2020; Woollen et al., 2012), they are less than 15 Mg ha^{-1} in treeless SBA lands (Magalhães, 2023; Montfort et al., 2021).

Given the fact that studies analyzing the impacts on SOC due to (1) WG conversion to SBA, (2) SBA conversion to CAFS are lacking for Mozambique and Southern Africa, and the fact that (3) CAFS establishment age does not always

FIGURE 1 Overview of the five land use systems in the study area in June 2022: coffee agroforestry systems (CAFS) in varied development stages (CA3, CA5, and CA8 as "a," "b," and "c"); wooded grasslands (WG, "d"), and slash-and-burn agriculture (SBA, "e"). CA3, CA5, and CA8 are coffee plantations aged 3, 5, and 8 years, respectively.

result in SOC enhancement, the current study was aimed at: (1) assessing the changes in SOC and the stratification ratio (SR) due to WG conversion to SBA and SBA conversion to CAFS, and (2) evaluate the age impact of shade-grown coffee plantations on SOC stocks. In that context, three hypotheses were set: (H1) WG conversion to SBA results in decreased organic SOC and SR; (H2) SBA conversion to CAFS results in increased SOC and SR; (H3) organic SOC and SR increase with the increasing age of the shade-grown coffee. The studied land use systems are illustrated in Figure 1.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area is located within the buffer zone of the GNP, in Gorongosa district (Canda locality), Sofala province, Mozambique (Figure 2), in the vicinities of Mount Gorongosa. The buffer zone spans over six districts and supports 250,000 people practicing subsistence farming (Gorongosa National Park, 2022, 2023). The mean annual rainfall is estimated at 1600 mm and is mostly distributed from December to February (MAE, 2005). The yearly mean air temperature is estimated at 22.5°C, ranging from 18°C to 26°C, with the mean maximum ranging from 25.5°C to 32.5°C, and the mean minimum from 10.5°C to 20°C (MAE, 2005). Lixisols are the predominant soils in the area (Driessen et al., 2001), which are strongly weathered soils with clay accumulation at depth, often requiring recurrent inputs of fertilizers and lime for arable farming. Examples of the sampled soil profiles are displayed in the supplemental material (Figure S1).

The Canda locality was mainly covered by WG in the colonial era (before 1975), and livestock grazing was the primary activity. During the civil war (1976–1992), the study area had negligible human impact. In the subsequent years, a

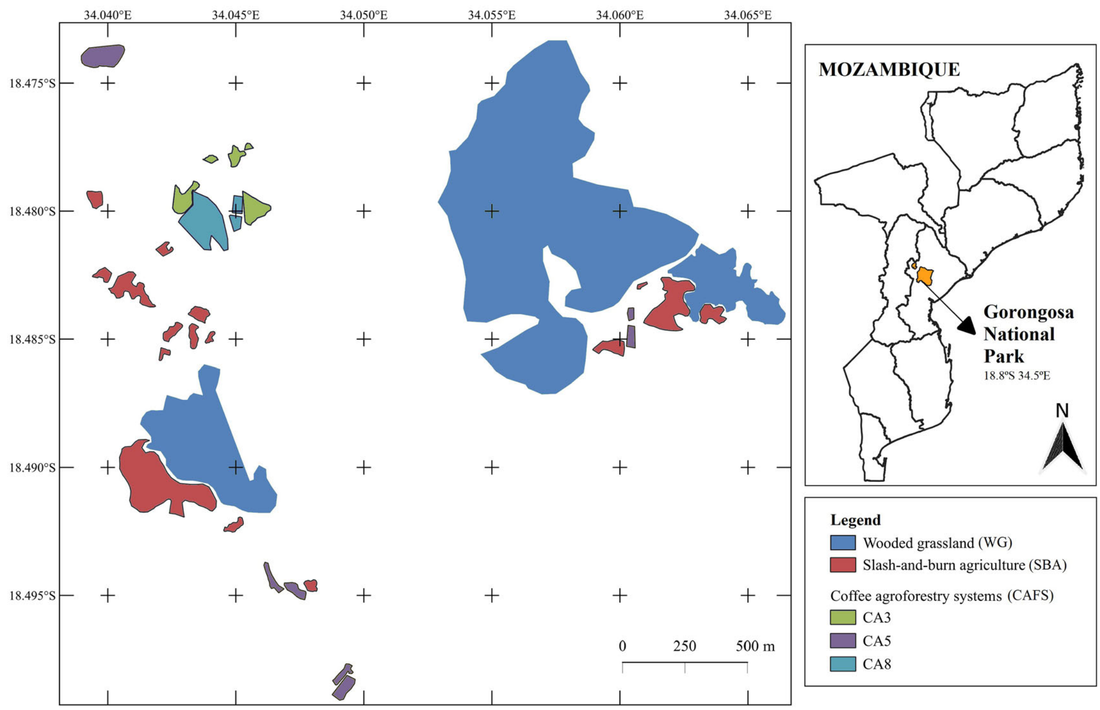

FIGURE 2 Study area location and spatial distribution of the investigated land use systems in the buffer zone of the Gorongosa National Park (Mozambique).

considerable area was converted into SBA lands. Lately, the GNP started a restorative agricultural venture with the local communities in 2013, by encouraging the conversion of SBA lands into CAFS. Currently, the area is a landscape mosaic consisting of aforementioned land uses.

In selected areas of the GNP buffer zone, Arabica coffee (*Coffea arabica* L.) is either planted, or found in agricultural fields, and intercropped with indigenous trees such as *Khaya anthotheca* (Welw.) C.DC., *Erythrina lysistemon* Hutch., *Albizia adianthifolia* (Schumach.) W.Wight, *Breonadia salicina* (Vahl) Hepper & J.R.I. Wood, *Millettia stuhlmannii* Taub., and *Bridelia micrantha* (Hochst.) Baill. At the time of field activities (June 2022), the GNP had installed 23 blocks of arabica coffee, in the Canda site, with tree ages up to 8 years old since the planting, and varied indigenous tree composition and structure consisting of trees far older than the established coffee trees.

2.2 | Land uses

The studied coffee and alternative land-use systems are described in Table 1. The CAFS are shade-grown coffee plantations aged 3, 5, and 8 years, respectively (CA3, CA5, and CA8), while slash-and-burn agriculture and local wooded grasslands are represented as SBA and WG. Tillage on the agricultural lands is accomplished by hoe, with no mechanical agitation and can be considered as no-till farming. Pruning is not applied to coffee shrubs, to prevent the occurrence of diseases, and neither to shade trees to maintain shade intensity. Nevertheless, the agroforestry sites are exposed to furtive wood removals (trees of lower dimensions, i.e., DBH < 15 cm), and well-developed branches are also often removed from trees of higher dimensions.

2.3 | Tree inventory

Shade trees were assessed using the *k*-tree sampling method (Kleinn & Vilcko, 2005; Nothdurft et al., 2010; West, 2021), also known as the *k*-nearest neighbor approach that provides rapid estimation of stand density and basal area (Husch et al., 2003; Kershaw et al., 2017). Here we used *k* set to six, hence the name "six-tree sampling" (Kleinn & Vilcko, 2005; Prodan, 1968) and six closest trees with a diameter at breast height (DBH, 1.3 m above the ground) ≥5 cm were selected as sample trees (Figure 3) and were measured for DBH and botanically identified. The distance of the sixth nearest tree defined the physical boundaries of the circular plot (radius), and so the sampled area was calculated (Kershaw et al., 2017; Nothdurft et al., 2010; Ramezani et al., 2016). As a result, the number of sample trees was fixed for each sampling location, whereas plot size changed according to patch-scale stem density. Eight random sampling points were allocated in each land use system. Finally, the cover of the herbaceous layer was estimated using a 2-m radius sub-plot applying the 10-point

TABLE 1 Summary description of studied land use systems and descriptive statistics of the measured variables.

Variable	Control groups		Treatments: shade coffee agroforestry systems (CAFS)		
	WG	**SBA**	**CA3**	**CA5**	**CA8**
Current land use system	Wooded grassland	Slash-and-burn agriculture	3 years old coffee shrubs (block 9)	5 years old coffee shrubs (block 7)	8 years old coffee shrubs (block 1)
Previous land use system	–	Wooded grassland	Shifting cultivation	Shifting cultivation	Shifting cultivation
Elevation (m asl)	975	969	956	966	936
Area (ha)	103	14	2	3	4
Stem density (stems ha^{-1})	107 ± 9	0	263 ± 8	236 ± 17	216 ± 23
Basal area (m^2 ha^{-1})	7.3 ± 1.1	0	5.37 ± 0.63	4.47 ± 0.88	5.87 ± 1.09
DBH range (cm)	10–77	–	10–63	10–20	7–59
Tree species count	15	0	13	4	5
Coffee plant spacing	–	–	2 m × 1.5 m	3 m × 1.5 m	3 m × 1.5 m
Coffee plant count	–	–	8374	2093	1762
Tree species	*Parinari curatellifolia* Planch. ex Benth. (31%) *Syzygium cordatum* Hochst. ex C. Krauss (25%) *Albizia adianthifolia* (Schumach.) W. Wight (21%)	–	*Persea americana* Mill. (27%) *A. adianthifolia* (19%)	*A. adianthifolia* (81%)	*A. adianthifolia* (69%)
Crop species	–	Maize (*Zea mays* L.)	*Coffea Arabica* L.	*Coffea Arabica* L.	*Coffea Arabica* L.
Grass cover (%)	91–100	91–100[a]	11–25	76–90	11–25

Note: Mean values followed by the standard error (±). Tree species proportion indicated in parentheses.
Abbreviation: DBH: diameter at breast height.
[a]Sampling occurred months after harvesting (high grass cover).

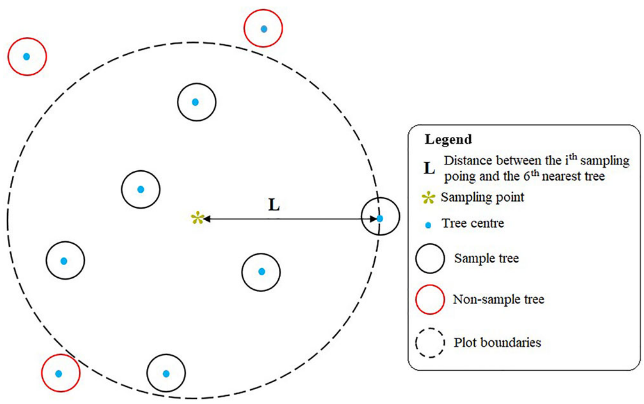

FIGURE 3 Six-tree sampling approach applied on sampling points (right next to soil profiles) to describe tree population in the studied land use systems.

Domin scale, which is a cover-abundance scale with predefined subdivisions to estipulate percentage cover of vegetation with uneven fixed ranges covering <4% (scale number 1, 2, and 3) to 91%–100% (scale number 10) (Kent, 2012).

2.4 | Soil organic carbon sampling

A soil pit was excavated to expose the soil profile at each sampling point (eight locations per land use) and sampled using the fixed depth (FD) approach. At five depths (D1: 0–20 cm, D2: 20–40 cm, D3: 40–60 cm, D4: 60–80 cm, and D5: 80–100 cm), disturbed soil samples were collected with garden shovels and spatulas. At each depth, a homogenized subsample of about 300 g was collected, placed in an air-tight polythene bag, labeled and sealed. Across all treatments and replicate pits, a total of 200 disturbed soil subsamples were taken to the laboratory for the determination of SOC concentration. Soil bulk density (BD) was undertaken by extracting soil cores from the profile at the same five depth layers using a 100 cm^3 volume corer (height: 51 mm, inner diameter: 50 mm). The soil cores were taken at the center for representativeness of the soil layer.

2.5 | Soil analysis

Disturbed soil subsamples were processed by oven-drying them at 105 ± 2˚C to constant mass, weighted, and ground to pass through a 2-mm sieve. These samples were used to determine the mass fraction of the rock fragments (>2 mm) (RF), and the FD-based SOC concentration. Soil organic matter (SOM) and FD-based SOC concentrations were determined by Walkley and Black method (Nelson & Sommers, 1982). Undisturbed soil samples were also oven-dried at 105 ± 2˚C to constant mass, and weighted. FD-based BD was obtained by dividing the dry-mass of the soil by the volume of the corer.

BD varies according to land use systems and management practices (Ellert & Bettany, 1995; Ellert et al., 2001). As a result, the sampled mass of soil per unit area varies (Wuest, 2009). Similarly, the amount of SOM added to the soil via biomass varies with land-use regimes and management practices, influencing the sampled volume of soil (von Haden et al., 2020). Because of the preceding, comparisons of SOC concentrations and stocks at FD intervals are prone to errors when BD or SOM vary, which is typical of terrestrial soils. Therefore, the equivalent soil mass (EMS) technique was applied to estimate SOC stocks based on the sampled FD-based soil data. By utilizing cubic spline interpolation models, the "*EMS* script" (Supporting Information; von Haden et al., 2020) was used to derive ESM-based SOC concentration and stocks. ESM-based cumulative SOC stock down to 1-m depth was obtained by summing the ESM-based SOC stocks of the five soil layers. Mean SOC accumulation rates were derived for the topsoil and 1-m depth among CAFS considering the age of the three systems. Finally, the SR was calculated by dividing the ESM-based SOC concentration of the surface depth layer (D1, top layer) by those of the lower depth layers (D2, D3, D4, and D5). Thus, four SRs were defined: $SR1 = SOC_{D1/D2}$, $SR2 = SOC_{D1/D3}$, $SR3 = SOC_{D1/D4}$, and $SR4 = SOC_{D1/D5}$.

Ellert et al. (2002) and Wendt and Hauser (2013) argued that SOC concentration and BD should be derived from the same soil samples for ESM-based SOC stock estimations purposes; however, in this work, those soil parameters were derived from distinct soil samples. ESM-based SOC stock estimations may contain inaccuracies if separate samples are used for BD and SOC concentration (von Haden et al., 2020). In this investigation, it is presumptive that such an error would be small. Hereafter, ESM-based SOC concentration and stock are simply referred to as SOC concentration and SOC stock, respectively. Even though the SOC concentrations and stocks are given on a FD basis, it is important to note that the ESM-based SOC concentrations and stocks reported in the results do not necessarily correspond to the sampled FD intervals; rather, they are estimated values that would have been obtained if the soil samples were taken to a common mineral soil mass.

2.6 | Statistical analysis

Shapiro–Wilk normality test was performed to detect departures from normality and revealed that the distribution of the soil data (BD and SOC) was not significantly different from normal distribution (p-value = 0.1086). Welch's one-way analysis of variance was then used to verify whether BD, SOC, and SR vary with land-use change (from WG to SBA and from SBA to CAFS at different ages) and within soil depths. The post hoc Games–Howell test was used to find pairs of means that were significantly different from each other. Wilcoxon test was also used to verify whether the SR values were statistically ≥2, as SR values >2 indicate higher soil quality and ratios <2 are frequently found in degraded soil (Franzluebbers, 2002). All statistical analyses were performed at $\alpha = 0.05$ using R (R Core Team, 2023). These analyses were performed under the assumption that initially (before the establishment of the coffee plantations), SOC stocks of CAFS were similar to that of remaining SBA lands, and SOC stocks of SBA lands were similar to that of WG lands.

3 | RESULTS

BD increased, and SOC concentration decreased, with increasing soil depth under each land use system and shade coffee plantation age (Figure 4). However, these variations were only significant at D1 and D2 (from 0 to 40 cm); no statistically significant differences in BD and SOC were found for layers D3, D4, and D5 (Figure 4).

BD and SOC stocks were found to vary among alternative systems (WG and SBA) and coffee plantation ages only in the surface soil layer (D1) (Figures 5 and 6): no significant differences were found in the deeper layers (D2, D3, D4, and D5). In the control groups WG and SBA, 36% and 38% of the SOC stock was found in the surface soil depth (D1), respectively. In the coffee systems, the age gradient (3–8 years, from CA3, CA5 to CA8) was mirrored by increasing SOC stocks from 35%, 44% to 52%, respectively, on the surface soil. Thus, more than 50% of SOC is stored in the subsurface layers (soil depths between 20 and 100 cm) for land use systems and coffee plantation ages, except coffee farms aged 8 years.

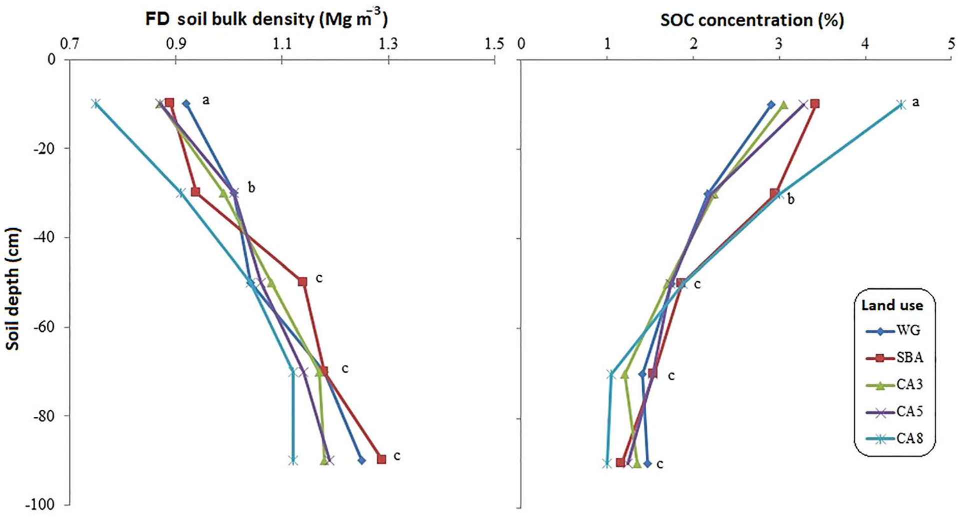

FIGURE 4 Fixed depth mean soil bulk density (left, BD) and mean soil organic carbon concentration (right, SOC) for the investigated land uses. Identical letters in a specific soil depth indicate statistical differences in the estimated means.

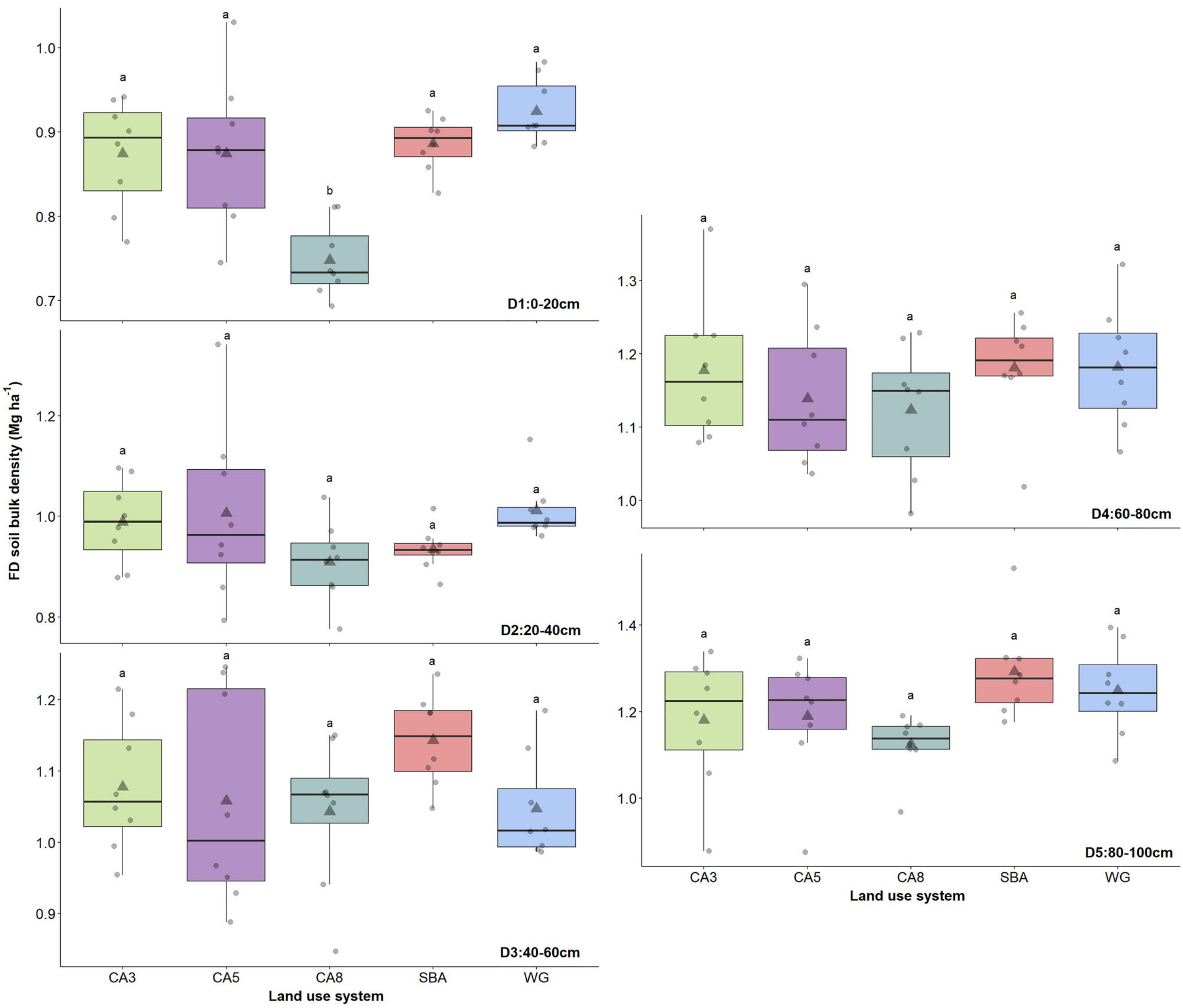

FIGURE 5 Fixed depth soil bulk density (BD) variation in the soil layers (D1, D2, D3, D4, and D5) for each land use system. Identical letters in a specific soil depth indicate statistical differences in the estimated means (triangles).

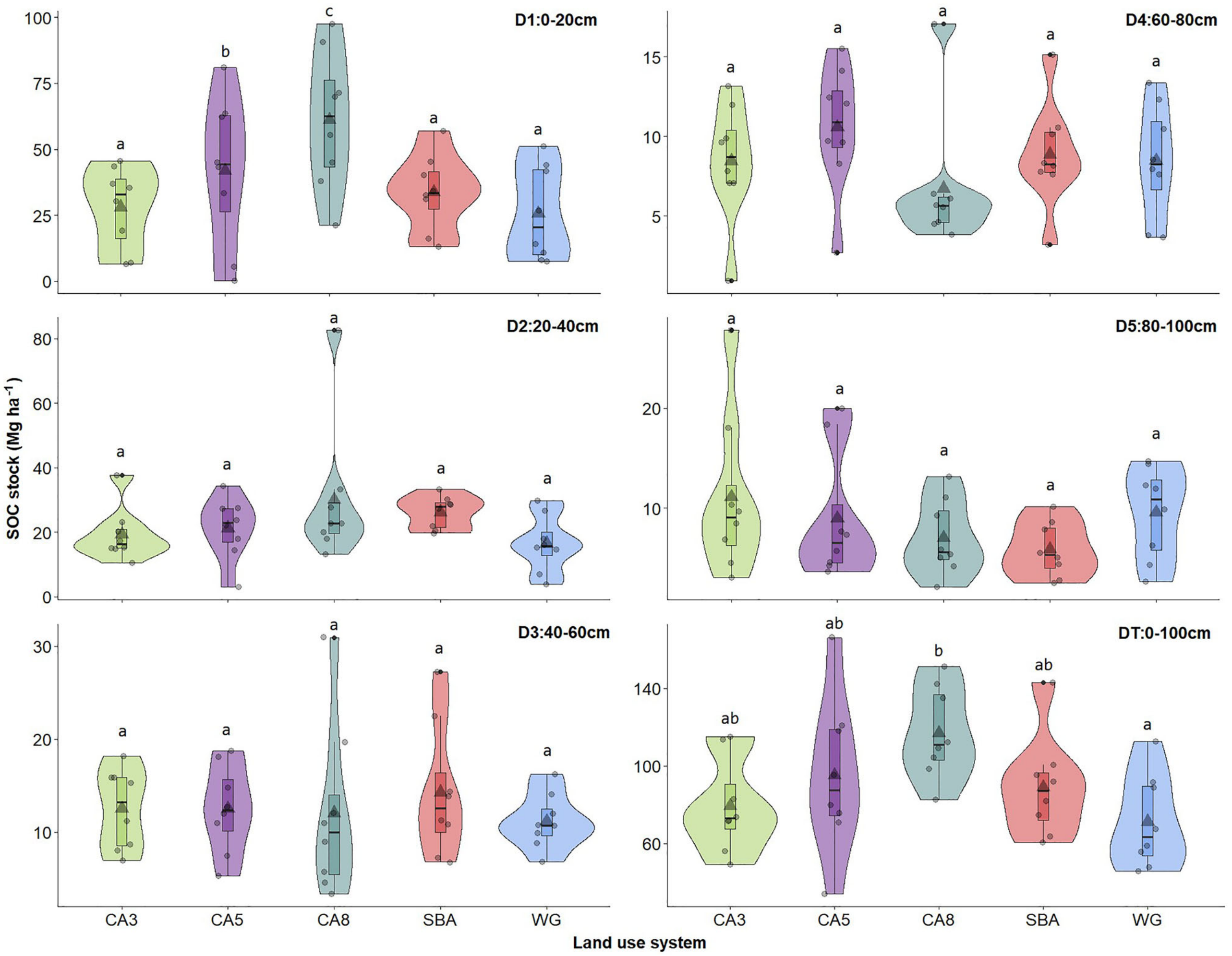

FIGURE 6 ESM-based soil organic carbon (SOC) stock in the soil layers (D1, D2, D3, D4, and D5) and profile (DT) for each land use system. Identical letters in a specific soil depth indicate statistical differences in the estimated means (triangles).

In the D1 layer, the 8-year-old coffee plantation (CA8) was significantly the lowest in BD; other treatments (WG, SBA, CA3, and CA5) did not statistically differ (Figure 5).

Although a 32% increase in SOC stock was observed with WG conversion to SBA, this increase was not statistically significant; a negligible difference was also observed 3 years (CA3) after SBA conversion to CAFS (Figure 6).

In the topsoil, statistically significant increases in SOC stock were first observed 5 years after SBA conversion to CAFS (Figure 6): CA5 soils were 24% and 64% significantly larger in SOC stock than SBA and WG soils, respectively (Figure 5). On the other hand, CA8 soils were 139%, 81%, 118%, and 46% greater in SOC stocks than WG, SBA, CA5, and CA3 soils, respectively (Figure 6). Surface SOC stocks were 25.6 and 33.7 Mg ha^{-1} in WG and SBA, and 28.0, 41.9, and 61.1 Mg ha^{-1} in CAFS (CA3, CA5, and CA8, respectively). The topsoil's mean SOC accumulation was 6.65 Mg ha^{-1} year^{-1}.

Total SOC stock followed the same trend as that of the topsoil (Figure 6). The 1-m-depth SOC stocks increased with CAFS development stage; from 3, 5 to 8 years after planting, stocks were 79.3, 95.2, and 117.0 Mg ha^{-1} (mean SOC accumulation of 7.59 Mg ha^{-1} year^{-1}), in contrast to alternative land uses systems SBA and WG with 89.0 and 71.2 Mg ha^{-1}. In general, the conversion of WG to SBA did not alter SOC stocks in any soil layer, disagreeing with hypothesis H1; however, the conversion of SBA to CAFS agreed with hypothesis H2, as it positively affected SOC stocks of the topsoil (Figure 6), and overcame those of the original vegetation (wooded grassland).

The SR increased with increasing soil depth (Figure 7), except that of WG, which decreased from D1 to D2. The SR for D1 to D2 (SR1) decreased with WG conversion to SBA (from 2.49 to 1.17) and increased following SBA conversion to CAFS, denoting an increase with coffee plantation age. In SBA and CA3, SR1 was found to be statistically <2; whereas that of WG, CA5, and CA8 were found to be statistically ≥2, denoting larger SOC values in the topsoil compared to those of the subsurface soils. Three years after SBA conversion to CAFS, SR1 still indicated soil degradation (SR = 1.40): no

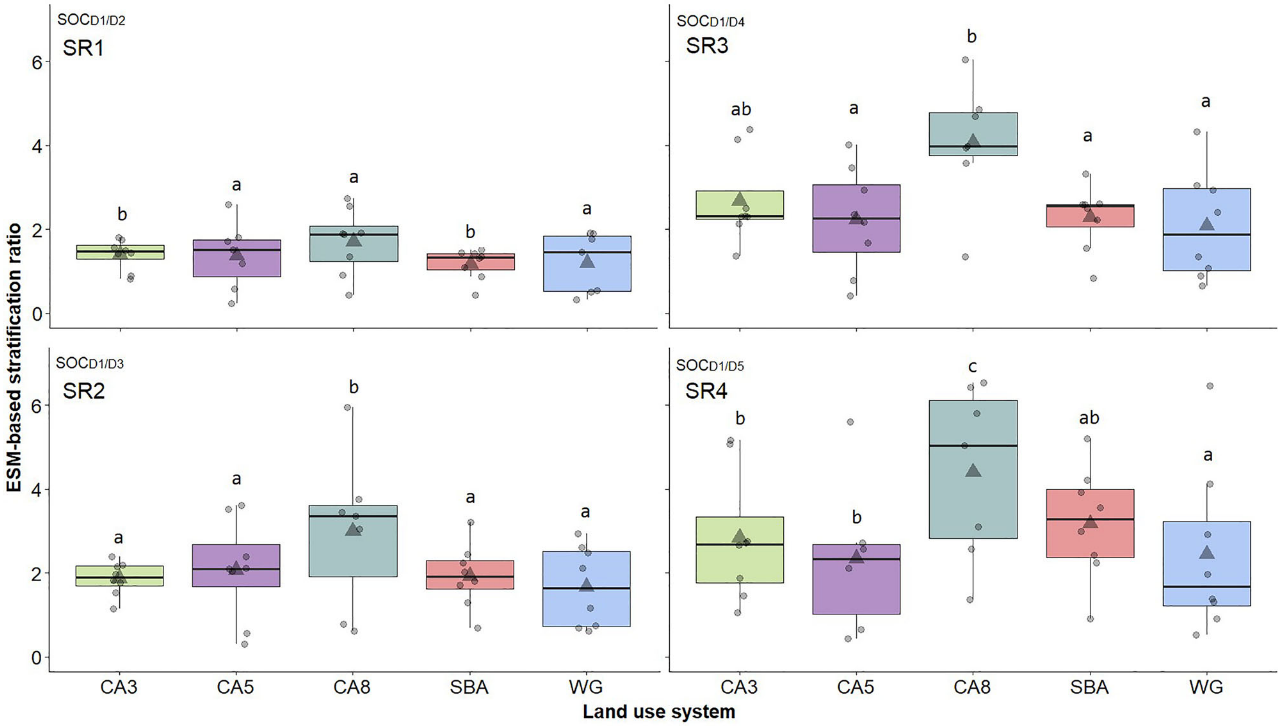

FIGURE 7 Stratification ratios (SR1, SR2, SR3, and SR4) for each land use system reflecting the SOC concentration between topsoil and deep soil layers. Identical letters in a specific soil depth indicate statistical differences in the estimated means.

tangible improvements were observed after 3 years of SBA replacement by shade-grown coffee.

Significant improvements in soil quality, as measured by SR1, were observed 5 years following SBA conversion to CAFS (Figure 7), recovering the quality of the original soil (WG soils). As regard to topsoil to deeper soils (SR2, SR3, and SR4), the SR was statistically ≥2. At whatever depth, the highest SR values were observed in the oldest CAFS (CA8).

4 | DISCUSSION

Previous research examining the relationship between BD and SOC change with soil depth (Bangroo et al., 2017; Corral-Fernández et al., 2013; Deng et al., 2016; Zhao et al., 2015) is consistent with the findings of this study, which showed an increase in BD and a decrease in SOC across all land use systems. BD and SOC changes following land-use change occur mainly in the surface soil (Biazin et al., 2018; Rolando et al., 2021; Wei et al., 2014), as the topsoil is most vulnerable to SOC loss or compaction due to land-use and management changes (Chatterjee et al., 2019; Jenkinson & Coleman, 2008; Noponen et al., 2013). This explains why there was no variation in BD and SOC between deeper soil layers (D3 to D5) of the same land use system and why BD and SOC were found to change solely in the surface soil layer (D1) across the concurrent land use systems (WG and SBA) and coffee plantation ages. Similarly to this work, Biazin et al. (2018), Wei et al. (2014), and Rolando et al. (2021) discovered that land use and land-use change only alter SOC in the superficial layer. Over a longer time period, the root system of shade trees might contribute to an increasing SOC in deeper soils layers, due to the turnover of deep roots; similarly to this study, Batjes (1996) and Jobbagy and Jackson (2000) observed that more than 50% of SOC was stored in subsurface soil layers.

The change in land use from WG to SBA had no effect on SOC stores, which is consistent with research by various authors (Bruun et al., 2021; Magalhães & Mamugy, 2020; McNicol et al., 2015) who discovered that conversion from naturally vegetated land to SBA results in unchanged SOC stock; however, it disagrees with studies reporting SOC changes with vegetated-land conversion to pure agricultural lands (Biazin et al., 2018; Durigan et al., 2017; Guo & Gifford, 2002; Laganière et al., 2010; Murty et al., 2002; Wei et al., 2014). According to Magalhães (2023), SOC is maintained following vegetated-land conversion to SBA fields when it results in a tree-based farming system (tree-based SBA), differently than in a treeless system. Similarly, Livesley et al. (2021) found soil carbon density to increase when Australian savanna is converted to pasture, but may not change under intense cropping systems.

According to practice directives of the GNP, weed removals and crop residues are either buried or used for mulching in SBA, being slowly incorporated to the soil. That fact explains why the conversion of WG to treeless SBA resulted in unchanged SOC stock. Surface fires are known to decrease soil organic matter (Armas-Herrera et al., 2018; Zhang & Biswas, 2017), and organic mulching and agricultural residue improve SOC accumulation (Fu et al., 2021; Haas et al., 2022; Iqbal et al., 2020; Sun et al., 2021; Wang et al., 2020).

Overall, this investigation supported hypothesis H3 since the SOC stocks of the superficial soil (0–20 cm layer) increased with increasing CAFS age, similar to the findings reported by Chatterjee et al. (2018). This is likely to be driven by increasing productivity and plant biomass accumulation with age, returning more organic carbon to the soil (Hombegowda et al., 2016); however, Chatterjee et al. (2019) did not support this pattern. This is in contrast to the findings of Noponen et al. (2013), who reported a decrease in SOC stocks after nine years of CAFS establishment, whereas we observed an increase in surface SOC with CAFS age. Conversion of SBA to CAFS caused SOC stocks in the top 20 cm to exceed those of the original savanna vegetation (WG), which is partially consistent with the findings of Hombegowda et al. (2016), who found that the implementation of CAFS in agricultural lands led to a rebound of SOC stocks to the levels of the original vegetation.

The current study's findings show that soil quality, as measured by SR, declined with WG conversion to SBA but improved with CAFS age, patterns commonly reported in degraded soils (Franzluebbers, 2002, 2010). Although this study assumes a small error derived from the use of separate samples for SOC concentration and bulk density (adjacent sampling positions), it is recommended that future studies consider deriving both parameters from the same soil samples. This practice, supported by Ellert et al. (2002) and Wendt and Hauser (2013), would ensure greater precision in SOC stock estimates, reducing possible inaccuracies and strengthening the validity of the results.

Even though repeated sampling before and after land-use change is desirable, the current study sought to investigate the response of SOC to anthropogenic land-use changes of WG to SBA and SBA to CAFS that occurred over a 47-year period (1975–2022). Therefore, a space-for-time substitution approach was applied, assuming that the sites were similar and in equilibrium prior to conversion (Rhoades et al., 2000): it was assumed that, initially (before the establishment of the coffee plantations), SOC of CAFS was similar to that of remaining SBA lands, and SOC of SBA lands was similar to that of WG lands. If these assumptions are not met, the results may be significantly biased. It is argued that these potential biases are minimized in this study because the soil and climate characteristics of the chosen study region are similar (Table 1; Figure S1), and the evaluated land-use systems are close to one another (50–1500 m, Figure 1) and in the same elevation range 936–975 m asl.

In this study, CAFS age was correlated with increasing SOC, but this finding is not universal as increasing aboveground C stocks by planting trees or perennial crops does not necessarily result in proportional increases in SOC (Chatterjee et al., 2019; Noponen et al., 2013). Future research should quantify leaf and fine root litter, assess leaf litterfall and fine root mortality for both shade trees and coffee shrubs, and model their relationship with biomass and CAFS age. It might be crucial to investigate the allocation of aboveground biomass in CAFS, considering trees and coffee shrubs separately.

5 | CONCLUSIONS

Given the paucity of studies on shade CAFS in Mozambique and Southern Africa, the SOC was evaluated based on soil samples collected from 40 1-m soil profiles. Further, the response of SOC to wooded grassland (WG) conversion to SBA, to SBA conversion to CAFS, and to ageing CAFS was also investigated. Changes in land use, land cover, and the stand development stage have affected BD and SOC only in the surface layer (0–20 cm; statistically significant). While BD of the surface layer did not change following WG conversion to SBA, it declined 8 years after CAFS replaced SBA. Regardless of the land use system, SOC stores were higher in the topsoil. Surface SOC stocks were not significantly altered following WG conversion to SBA, though they increased with the conversion of SBA to CAFS, and with increasing age of CAFS. Total SOC stocks raised approximately 7.59 Mg ha^{-1} year^{-1} with increasing coffee age; and the 8-year-old coffee had the greatest mean SOC stock (117.0 Mg ha^{-1}). As an indicator of soil quality, the SR was found to deteriorate following WG conversion to SBA, and to recover with the replacement of SBA by CAFS, improving gradually as these systems aged. This study reveals that CAFS have the potential to increase belowground carbon sequestration when compared to SBA and WG, making it a viable option for climate change mitigation, while simultaneously generating revenue from coffee beans.

AUTHOR CONTRIBUTIONS

Tarquinio Mateus Magalhães: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; supervision; writing—original draft; writing—review and editing. **Rafael Bohn Reckziegel**: Conceptualization; funding acquisition; Investigation; methodology; visualization; writing—review and editing. **João Paulino**: Investigation; methodology.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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