


Article

Differential Impacts of Cropland Expansion on Soil Biological Indicators in Two Ecological Zones

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Abstract: Agricultural expansion in Sub-Saharan Africa is characterized by different farm ages in smallholder communities. This study investigated changes in microbial indices broadly (i) at the reconnaissance survey level in four agro-ecological zones and (ii) in different farms at the forest (Dompem) and forest–savanna transition (Adansam) zones, as influenced by the duration of cultivation. Soils from one-year (first cultivation of cleared forest/fallow), three-year, five-year, and ten-year farms were analyzed for basic soil properties, active or labile carbon (POXC), basal respiration (BR), microbial biomass (C_{mic}) using permanganate oxidizable C, alkali trap, and chloroform fumigation incubation. In both study levels, POXC content was <1% of soil organic carbon (SOC) in all zones, higher in the wet agro-ecological zones, and positively correlated with SOC ($r = 0.70, 0.81; p < 0.01, p < 0.001$). Dompem SOC and BR declined by 1–23% and 6–25% ($p < 0.001$), respectively, in the first three years; C_{mic} ($p = 0.002$) and $\%C_{mic}/SOC$ ($p = 0.610$) decreased from three-year farms onwards. Conversely, the Adansam SOC, BR, C_{mic} , and $\%C_{mic}/SOC$ rather had irregular trends. The microbial indices were influenced by exchangeable acidity, the sum of exchangeable bases, and effective cation exchangeable capacity negatively or positively, followed by SOC, pedogenic compounds, particularly dithionite-citrate iron (Fe_d), oxalate iron (Fe_{ox}), and lastly, soil pH. Therefore, understanding the degree, direction, and changing aspects of these drivers of soil ecosystem services is necessary for sustainable soil management practices in different agro-ecological zones.

Keywords: basal respiration; farm types; labile carbon; metabolic quotient; microbial biomass



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1. Introduction

Cropland expansion occurs within a loop of drivers [1] and impacts [2–4]. Most of the impacts have been widely known and are mostly associated with booms and busts [5,6] as well as trade-offs, such as low, long-term real income levels per capita [5], the loss of biodiversity, and reduced carbon stocks [6–8]. The trade-offs are attributed to negative impacts resulting from a decline in the delivery of ecosystem services, although synergies have also been found [3,9,10]. Other negative impacts of cropland expansion range from changes in land quality [11] to nutrient losses with decreased agricultural productivity and soil ecosystem services [12,13], mostly caused by huge nutrient exports and a reduced capacity for recycling [14–16] caused by above and belowground carbon losses [15–18]. Interestingly, the nature of the impacts presents diverse spatial variability [9] depending on the region under consideration [9,17] and the spatial pattern of conversion defined by time after conversion and location, i.e., forest interiors, from forests edges into forests [19].

Most of the impacts of cropland expansion have been either examined at different scales [9,20,21] or compartmentalized [22] and mostly focused on the aboveground natural environment and its ecosystem services [13,22,23]. Research on the effects of agricultural expansion is widespread [4,4,10–12,24]. However, there is a huge focus on aboveground

biodiversity [4,4], socio-economic impacts, policy, and governance [10], broad land issues [11,24], carbon storage, and climate [17,24]. Sadly, less attention has been given to the belowground environment, though there is evidence that land use drives soil microbial properties [7,25], land clearing affects soil, and micro-climate [26], which all strongly affect soil ecosystem services. The ecosystem services provided by soils cannot be underestimated or overlooked since a decline in the supporting services is one of the drivers of yield gaps [27,28] and cropland expansion [10,29,30]. This is strongly manifested in Sun-Saharan Africa (SSA), where crop yields are increased marginally through increased farm size compared to intense inputs utilization per unit area in other continents [23,31]. In addition, land rotation is widely practiced as an upgraded form of shifting cultivation caused by soil fertility decline and its associated yield decline. Research shows that there is a link between aboveground and belowground biodiversity [32–36]. This implies that an effect on aboveground biodiversity also affects belowground biodiversity. This relationship occurs through C supply and the alteration of micro-habitat conditions [37]. It was found that the plant species' effect on belowground biodiversity is below that of soil type [38]. Furthermore, there may be disconnects between the link to specific ecosystem services that vary with regional differences. For instance, Felix et al. [9] found a high spatial variation in the impacts of agricultural expansion across Europe. Narrowing onto C losses, it is estimated that about twice the amount of C lost in temperate regions is lost in the tropics. Specifically, one hectare of land cleared in the tropics releases about 120 tons of C annually but produces only 1.7 tons of crops (dry weight) compared to 63 tons of C loss with an annual crop production of 3.8 tons [8]. These have been attributed to conventional tillage and rapid decomposition in the tropics (Nunes et al., 2011), cited by Souza et al. [39]. It is worth appreciating the strong nexus between soil organic carbon (SOC) and soil biology, and the latter is the energy source of the food chain in the soil environment. Previous studies have found that converting native vegetation to cropland had no effect on total C and N within 1 m depth, but it affected C dynamics, causing soil health decline [14]. This is because these trade-offs tend to vary with the type of ecosystem cleared, soil type, and crops grown, as well as soil and crop management practices employed [8]. Earlier research on farm types under agricultural expansion in the forest zone of Ghana showed a decline in SOC with farm age, which occurred along with a decline in soil charge properties [40]. This pattern differed from each of the two agro-ecological zones studied. In a four-stage Argentine chronosequence, Tosi et al. [41] observed a huge effect on the functionality and biomass of soil microbial communities during the first years of cultivation.

Thus, the link between the aboveground and belowground biodiversities and the high spatial variability implies that the effect varies from place to place. It was hypothesized that cropland expansion tends to exert different pressures on the aboveground and belowground ecosystems in different cropping patterns, soils and soil management regimes, and agro-ecological zones. Therefore, cropland expansion manifested as land rotation yielding farms of different ages have variable effects on microbial-related soil properties. The objectives of this study were to investigate whether the effects of agricultural expansion on microbial soil properties present the same patterns of variability across the agro-ecological zones and whether the variability has innate relationships with the various factors associated with the unique ecosystems in each agro-ecological zone. Microbial properties are indicators of soil ecosystem health, soil quality, and biodiversity, which play a huge role in the delivery of almost all the ecosystem services provided by soil [42–44]. Therefore, the significance of this study is that it can (a) provide an indication of ecosystem health, (b) yield insights into ecosystem-specific long-term soil and environmental management strategies to enhance worldwide sustainability in resource utilization and continued supply of ecosystem services, and (c) ultimately contribute to the achievements of the sustainable development goals.

2. Materials and Methods

2.1. Study Sites and Sampling

Considering the differences in spatial variability and patterns of conversion, a reconnaissance survey was first conducted, after which two study sites were selected from the two agro-ecological zones. Consequently, the study was conducted at reconnaissance survey sites in four agro-ecological zones (see Figure 1) and in more detail at farm age levels in the Dompem–Pepesa area ($5^{\circ}09'33.7''$ N; $2^{\circ}04'29.4''$ W), located in the Tarkwa–Nsuaem Municipality in the forest zone, and the Adansam–Kokuma area ($7^{\circ}50'35.9''$ N, $1^{\circ}45'59.9''$ W) within the Kintampo South District in the forest–savanna transition zone of Ghana (lower panel Figure 1). At each site, sixty farms of different ages were considered. These include newly cleared native vegetation or fallow (one year), then three, five, and ten years of cultivation. Details of site selection, description, and sampling can be found in Figure 1 and in previous studies by Neina and Agyarko-Mintah [40] and Neina and Adolph [45].

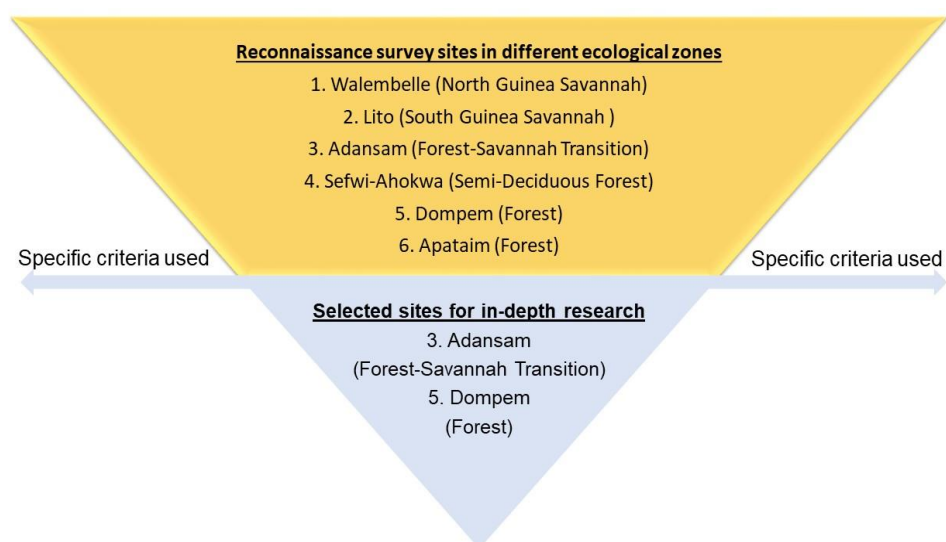


Figure 1. Site selection scheme: Details of the selection criteria can be found in Neina and Agyarko-Mintah [40] and Neina and Adolph [45].

2.2. Laboratory Procedures

2.2.1. Analysis of Basic Soil Properties

Standard laboratory analyses were employed to measure basic soil properties, such as bulk density; particle size; pH in water and in KCl; total carbon (C), nitrogen (N), and sulfur (S); basic cation contents; exchangeable acidity; and pedogenic compounds, i.e., dithionite-citrate-bicarbonate and oxalate-extractable Al and Fe. The procedures were already described and reported by Neina and Agyarko-Mintah [40] and Neina and Adolph [45]. The soils contained no calcium carbonate. Thus, the total C contents were considered to be soil organic carbon (SOC).

2.2.2. Labile C, Basal Respiration, and Microbial Biomass

The labile C contents of the soils, measured as permanganate oxidizable carbon (POXC), were determined using the Weil et al. [46]–modified method of Blair et al. [47]. The basal respiration was measured from fresh soils stored at 4°C using the Isermeyer [48] alkali method. The soils were adjusted to 50% water holding capacity (WHC) and pre-incubated to allow equilibration with the ambient environment. Afterward, 100 g of soil were weighed into 100 mL plastic cups and placed in 1.2 L glass jars with air-tight lids. Glass vials containing 10 mL 0.25 M KOH were placed in the jars and incubated in the dark at 28°C according to Creamer et al. [49] for seven days. This temperature was also chosen because it is close to the average ambient temperatures of the ecological zones. To measure

the microbial biomass, the chloroform fumigation extraction method of Brookes et al. [50] was first tested. However, it failed probably because of the low SOC contents, low pH of some, and uncertainties associated with the extraction efficiency of 0.5 M K₂SO₄ [51]. Therefore, the chloroform fumigation incubation method [52] was used. Two sets of 40 g of fresh soil adjusted to 50% WHC were weighed into plastic cups. One set was fumigated with ethanol-free chloroform, while the other set was equally placed in vacuum desiccators for 24 h. After fumigation, the fumigated set was inoculated with 1 g of fresh soil. Both sets were incubated in 1.2 L glass jars and along with 0.25 M KOH in glass vials. The jars were tightly closed and incubated for 10 days at 28 °C, followed by back titration after precipitation with BaCl₂.

2.3. Statistical Analysis

For the statistical analysis, 10 to 11 farm replicates per farm type were obtained from Adansam, whereas 9 to 10 farm replicates were obtained from Dompem. The data were assessed for their conformity to the analysis of variance (ANOVA) before subjecting them to one-way ANOVA, followed by means separation, where necessary, using a Tukey HSD 5% significance level. Where possible, non-normal data were square-root, log, or ln transformed before further analysis. Where data were not normally distributed, Kruskal–Wallis [53] and Mann–Whitney U tests were used for analysis [54]. In addition to ANOVA, Pearson and Spearman correlation analyses [54] were run to determine the effects of the farm types on measured properties and relationships between basic soil properties and the microbial indices. The statistical analyses were conducted using SPSS version 20 (IBM® SPSS® Statistics, New York, NY, USA), whereas the graphs were produced using Sigma Plot 13 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Basic Soil Properties

Previous studies on the same sites and soils have already presented data on the basic properties of the reconnaissance sites in the various ecological zones [45] and two study sites [40], where more details can be found. The soils are sandier in the northern half and less sandy in the southern part of the country. The SOC contents of the reconnaissance survey sites varied widely, showing significant differences ($p = 0.014$). The semi-deciduous forest zone had about twice the SOC contents of the other zones, with the least content found in the forest–savanna transition zone (Table 1). Generally, the soils of the two selected study sites were acidic, although the Adansam soils were slightly acidic, whereas the Dompem soils had very strong acidity with a mean difference of 1.9 pH units. The Dompem soils are fine-textured soils while the Adansam soils are slightly coarse-textured (Table 2). The Dompem soils had about twice the SOC contents of the Adansam soils, showing no significant differences ($p > 0.05$) among the farm types. However, the first-year cultivation (freshly cleared forests or fallows) of both study sites had 6.7 to 11.7 g kg^{−1} and 1.3 to 1.9 g kg^{−1} more SOC than the older farms in the Dompem and Adansam soils, respectively. Whereas the SOC of the Dompem farms did not differ ($p = 0.050$) from each other, those of Adansam differed significantly ($p = 0.008$) (Table 2).

Table 1. SOC and microbial indices of the reconnaissance survey sites in the various ecological zones of Ghana (N = 3/4).

Ecological Zone	¹ SOC	POXC	POXC/SOC	CO ₂ -C	C _{mic}	C _{mic} /SOC	qCO ₂
	mg kg ^{−1}	%	μg g ^{−1}		%		
Forest–savanna transition (Adansam)	5.86 a	46.71 a	0.82 a	25.60 a	70.11 a	1.31	0.40 a
Semi-deciduous forest (Sefwi-Ahokwa)	17.03 b	73.72 b	0.44 b	55.12 b	52.65 a	0.33	1.09 b
South Guinea savanna (Lito)	8.90 a	33.08 a	0.38 b	27.79 a	145.25 b	1.75	0.18 a

Table 1. Cont.

Ecological Zone	¹ SOC	POXC	POXC/SOC	CO ₂ -C	C _{mic}	C _{mic} /SOC	qCO ₂
	mg kg ⁻¹	%	μg g ⁻¹		%		
North Guinea savanna (Wallembele)	10.81 a	27.96 a	0.27 b	28.81 a	115.46 c	1.24	0.25 a
CV (%)	51	44	59	46	47	66	84
p-Value	0.014	0.001	0.020	0.017	0.007	0.126	0.002

¹ Data overlap with part of C data published in Neina and Agyarko-Mintah [40] because only farms with specific SOC contents were used for the incubation in this study. Therefore, the mean values reported here differ slightly. Data in columns followed by different letters depict significant differences at p -value < 0.05. The reconnaissance survey data of Dompem (Forest zone) were excluded here.

Table 2. Soil pH, SOC, POXC, and its fraction in total C and textural classes of the Adansam (N = 10/11 (SE)) and Dompem (N = 9/10 (SE)) soils.

Farm Type	¹ pH	SOC	POXC	POXC/SOC
	Water	g kg ⁻¹	mg kg ⁻¹	%
Dompem				
Year one (forest)	4.3 (0.16)	28.49 (5.60)	64.82 (6.90)	0.26 (0.00) a
Year one (fallow)	4.3 (0.15)	21.81 (1.81)	67.03 (4.02)	0.32 (0.00) b
Three years	4.4 (0.14)	21.43 (3.70)	53.91 (7.21)	0.26 (0.00) a
Five years	4.5 (0.13)	16.82 (1.16)	65.06 (5.22)	0.39 (0.00) b
Ten years	4.5 (0.13)	16.89 (2.45)	52.01 (3.82)	0.33 (0.00) b
p-value	-	0.086	0.175	0.001
Adansam				
Year one (forest/fallow)	6.3 (0.08)	12.23 (0.63) a	47.27 (2.85)	0.39 (0.00)
Three years	6.2 (0.15)	10.29 (0.70) a	38.03 (4.93)	0.36 (0.00)
Five years	6.4 (0.13)	8.79 (0.69) b	36.61 (2.36)	0.43 (0.00)
Ten years	6.3 (0.17)	10.91 (0.73) a	38.85 (2.55)	0.37 (0.00)
p-value	-	0.008	0.100	0.482

¹ Part of the data was published in Neina and Agyarko-Mintah [40] because only farms with specific SOC contents were used for the incubation in this study. Therefore, the mean values reported here differ slightly. Data in columns followed by different letters depict significant differences at p -value < 0.05. Data in parentheses represent the standard error of means.

3.2. Labile C, Basal Respiration, and Microbial Biomass

In both stages of the study, the POXC content was higher in the wet agro-ecological zones. For the reconnaissance survey sites, POXC ranged from 28 to 74 mg kg⁻¹. The semi-deciduous forest zone had the highest content, which was about 27 to 45 mg kg⁻¹ more POXC than the other zones (Table 1). The lowest POXC content was found in the Northern Guinea savanna zone. The POXC fraction of SOC was <1% in all zones ranging from 0.27 to 0.82%, with the highest occurring in the forest–savanna transition zone. In the main study of the two selected sites, the Dompem soils had 20 mg kg⁻¹ more POXC content with significant differences ($p = 0.001$) among the farm types but showed no particular trend. The fractions of POXC in the SOC were generally <1%, not even up to 0.5%. The Adansam soils had higher fractions of POXC in their SOC than the Dompem soils (Table 2). POXC correlated positively with the SOC of both the Adansam soils ($r = 0.70$, $p < 0.01$) and the Dompem soils ($r = 0.81$, $p < 0.001$) (Figure 2).

Again, the wet agro-ecological zones had the highest basal respiration. Among the reconnaissance survey sites, the semi-deciduous forest zone had the highest amount of basal respiration, which was 1.9 to 2-fold that of the other zones (Table 1). The order was semi-deciduous forest > Northern Guinea savanna > Southern Guinea savanna > forest–savanna transition zones. Of the two study sites, Dompem soils had 22.8 μg g⁻¹ more basal respiration than the Adansam soils, showing significant differences ($p < 0.002$) among the farm types. An increasing trend was observed from the three-year-old farms toward the ten-year-old farms (Figure 3). The Adansam soils rather showed more irregularity, with significant differences ($p < 0.001$) among the farm types.

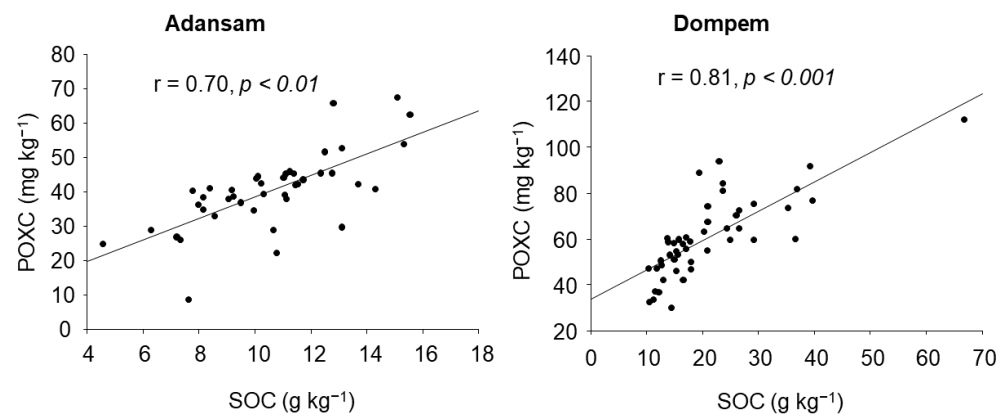


Figure 2. Pearson correlation between SOC and POXC for the Adansam (left) and Spearman for the Dompem (right) soils.

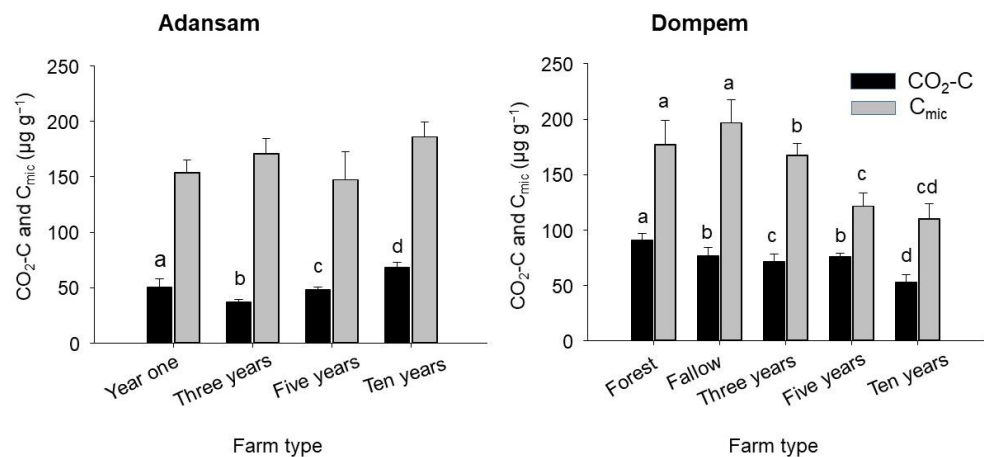


Figure 3. Basal respiration ($p < 0.001$) and C_{mic} ($p = 0.109$; $p = 0.002$) of the farm types from Adansam (left) and Dompem (right). Bars of the same color followed by different letters depict significant differences at p -value < 0.05 .

In contrast to basal respiration, the microbial biomass (C_{mic}) of the reconnaissance sites was highest in soils of the Southern Guinea savanna, followed by Northern Guinea savanna, forest–savanna transition, and semi-deciduous forest zones (Table 1). The mean C_{mic} of the Adansam soils was $10 \mu\text{g g}^{-1}$ higher than that of the Dompem soils but did not differ ($p = 0.109$) among the farm types (Figure 3). The C_{mic} of the Dompem soils differed ($p < 0.05$) among farm types and showed a decreasing trend from the three-year-old farms (Figure 3). The fractions of C_{mic} in the SOC of the reconnaissance survey sites followed the same pattern as the C_{mic} and were mostly $>1\%$ (Table 1). For the two sites, the Dompem soils had more C_{mic} in the range of 0.7 to 0.9% compared to 0.4 to 0.7% in the Adansam soils (Figure 4). While the $\%C_{mic}/\text{SOC}$ of the Adansam soils differed ($p = 0.002$) among farm types and showed an increasing trend from the three-year-old farms, it did not differ ($p < 0.05$) in the Dompem soils but decreased from the fallow farms toward the ten-year old farms. The metabolic quotient ($q\text{CO}_2$) ranged from 0.18 to 1.09 for all the study sites (Table 1 and Figure 5) and was higher in the semi-deciduous forest of the reconnaissance survey sites and in the Dompem soils. The trend was irregular at the two sites, but the farm types on the Dompem soils differed significantly ($p = 0.027$) from each other (Figure 5).

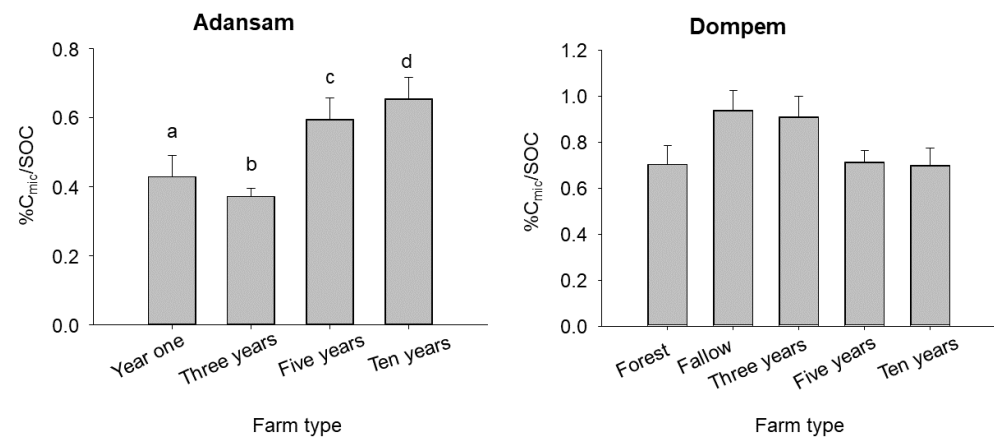


Figure 4. The fraction of microbial biomass in the SOC ($\%C_{mic}/C$) of soils from different farm types of Adansam ($p = 0.002$) (left) and Dompem ($p = 0.610$) (right). Bars followed by different letters depict significant differences at p -value < 0.05 .

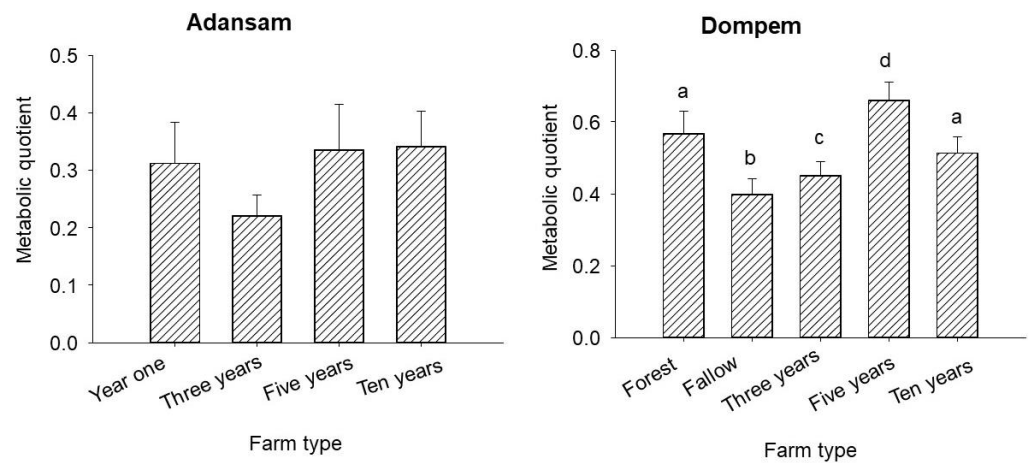


Figure 5. Metabolic quotient (qCO_2) in soils of the farm types from Adansam ($p = 0.154$) (left) and Dompem ($p = 0.027$) (right). Bars followed by different letters depict significant differences at p -value < 0.05 .

3.3. Effect of the Basic Soil Properties on Microbial Indices

The correlation analysis showed that the basic soil properties played key roles in the POXC contents and its fraction in SOC, basal respiration, and microbial biomass, and qCO_2 , particularly in the soils of the reconnaissance survey. The exchangeable acidity (EA), the sum of exchangeable bases (SEB), and the effective cation exchangeable capacity (ECEC) had the most influences, either negative or positive (Table 3), followed by SOC, pedogenic compounds, particularly Fe_d and Fe_{ox} , and lastly soil pH. The EA correlated positively with POXC, $\%POXC/SOC$, CO_2-C , C_{mic} , and qCO_2 but correlated negatively with $\%C_{mic}/C$ (Table 3). The SEB and ECEC correlated positively with POXC, CO_2-C , and qCO_2 , but correlated negatively with C_{mic} and $\%C_{mic}/SOC$. Among the pedogenic compounds, only Fe_d and Fe_{ox} had negative effects on the microbial indices. Only the basal respiration of the Dompem soils correlated positively with SOC ($r = 0.42$, $p = 0.003$), POXC ($r = 0.31$, $p = 0.032$), and ECEC ($r = 0.33$, $p = 0.023$) but correlated negatively with Al_d ($r = -0.35$, $p < 0.01$). No useful correlations were found in the Adansam soils.

Table 3. Pearson and Spearman correlation coefficients for the reconnaissance survey soils.

	POXC	%POXC/SOC	CO ₂ -C	C _{mic}	qCO ₂	%C _{mic} /SOC
pH	0.20 ns	-	-	-0.47 ns	-	-0.34 ns
SOC	0.50 ns	-0.66 *	0.76 **	-	0.39 ns	-0.66 *
EA	0.46 ns	-	0.57 *	0.60 *	0.61 *	-0.54 *
ECEC	0.73 **	-	0.54 *	-0.63 *	0.66 *	-0.71 **
SEB	0.73 **	-	0.68 **	-0.64 *	0.68 **	-0.70 **
Al _d	-0.43 ns	-0.26 ns	-	-	-	-
Al _{ox}	-0.20 ns	-0.21 ns	-	-	-	-
Fe _d	-0.91 ***	-0.68 **	-0.45 ns	0.62 *	-0.59 *	0.37 ns
Fe _{ox}	-0.43 ns	-0.79 **	-	0.28 ns	-	-

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant; SOC = soil organic carbon; EA = exchangeable acidity; CEC = effective; SEB = sum of basic cations; Al_d and Al_{ox} = dithionite-citrate and oxalate-extractable aluminium, respectively; Fe_d and Fe_{ox} = dithionite-citrate and oxalate-extractable iron, respectively.

4. Discussion

The results of the two stages of the study confirmed our hypothesis that agricultural expansion tends to exert different pressures on the aboveground and belowground ecosystem in different cropping patterns, soils and soil management regimes, and agro-ecological zones. This was observed by Cao et al. [55], who concluded that major soil microbial groups have distinct biogeographic patterns in different agro-ecological zones. Our results present a picture of interactions between external environmental and edaphic factors categorized as eco-edaphic trends and farm trends, starting from a broad (reconnaissance survey) to a narrow (main study) level. The eco-edaphic trends present diverse edaphic conditions in each agro-ecological zone, particularly with regards to SOC, POXC, soil texture, and pH, as seen in this and previous studies [40,45] on the same study sites. For instance, the findings of the reconnaissance survey sites show that the wet zones (forest and deciduous forest) contained more SOC and POXC than the forest–savanna transition and two savanna zones. These are in agreement with the findings of Smith et al. [56], Leng et al. [57], and Duval et al. [58]. Briefly, the edaphic conditions of the agro-ecological zones are described as follows [45]:

- Forest zone—clay loams/sandy clay loam textures with very strong acidity;
- Deciduous forest—sandy clay loams with slight acidity;
- Forest–savanna transition—sands with slight acidity;
- Southern Guinea savanna—sandy loams with strong acidity;
- Northern Guinea savanna zones—sandy loam with slight acidity; and
- Finally, the Adansam soils were arenic/sandy with slight acidity, while the Dompem soils were loams with very strong acidity [40].

The farm trends have two aspects, that is, numerical declines in the properties with and without statistical differences among the farm types. It is observed that the Adansam soils SOC and POXC contents decreased up to the five-year-old farms and increased again in the ten-year-old farms (Table 2), but only the SOC contents differed ($p = 0.008$) among farm types. Meanwhile, the basal respiration and %C_{mic}/SOC decreased in the three-year-old farms and increased in the five-year-old farms onwards. In both cases, the farm types differed ($p < 0.05$) from each other. Conversely, the SOC of the Dompem soils decreased up to the five-year-old farms with no significant differences ($p = 0.086$); the C_{mic} decreased, showing differences ($p = 0.002$) among the farm types compared to %C_{mic}/SOC, which also decreased but without significant differences ($p = 0.610$). The decreasing trends in some soil properties were observed in Mollisols and Vertisols by Tosi et al. [41], who found higher basal respiration within three years of cultivation, where native vegetation soils lost 50–80% C_{mic} within 30 years of cultivation while %C_{mic}/SOC declined within three years of cultivation and stabilized from 13 to 30 years of cultivation. In this study, we also observed decreasing trends in the fine-textured soils of the forest zone, whereas irregular trends were found in the sands of the forest–savanna transition zone. Interestingly, a clear contrast is

observed between the cleared forests and fallows of the Dompem soils. This observation may be due to the nature of the forests, which are characterized by thick canopies and root turfs that cover the forest floors. These limit rain through fall, soil aeration, and water infiltration, which affect SOC decomposition and accumulation. Consequently, when such forests are freshly cleared, the SOC content is usually small unless the debris decomposes to increase the SOC content.

Comparing the values with those of other studies, the higher SOC, POXC, and basal respiration found in the wet agro-ecological zones confirm the positive correlations between SOC and POXC in the two sites, which corroborates the findings of [56,58–60]. The POXC values found were 11–28% of the POXC values found by Bongiorno et al. [60], Duval et al. [58], and Ramirez et al. [61]. In addition, the %POXC/SOC found in this study was much lower than that found by Bongiorno et al. [60], Duval et al. [58], Ramirez et al. [61], and Culman et al. [59]. The range of basal respiration values was low, in the same range, or higher than those found in Rwandan and Argentine soils [41,62]. Furthermore, there was more %C_{mic}/SOC in the study soils than in the acidic Rwandan soils [62], but it was only a fraction of those found by Tosi et al. [41]. The values were not up to 1% of SOC, that is, half of the maximum 2% C_{mic} contained in SOC [59]. The $q\text{CO}_2$ values found in this study were highly variable and were either lower or higher than those of Tosi et al. [41]. Xu et al. [63] also found low values in tropical/subtropical soils. The $q\text{CO}_2$ is an ecosystem soil health indicator. The values obtained are said to be characteristic of healthy agricultural soils [56,64,65]. The $q\text{CO}_2$ of the Adansam soils, Dompem fallow, and three-year-old farms suggest a high microbial C use efficiency, where a greater portion of the microbial communities is not involved in nutrient cycling or C sequestration [64]. Soil properties such as EA, SEB, and ECEC enhanced $q\text{CO}_2$, whereas Fe_d reduced it across the agro-ecological zones (Table 3). Other studies found SOC and pH as the most important soil factors influencing $q\text{CO}_2$ [63].

As an edaphic ecosystem energy resource, POXC is described as a footprint of soil properties that controls the supporting and regulating ecosystem services of soils [60]. POXC is related to C_{mic}, which varies from strong to weak depending on the location [59]. This variation is linked to both edaphic and external ecological factors. In soils of different land use systems and ecoregions, soil attributes such as soil pH and nutrient status accounted for about 31% of the variation in microbial communities studied [55,66]. Although we did not measure the structure of microbial communities in this study, it is possible that the relatively high C_{mic} in the Adansam soils is attributed to a higher fungal population, as fungi contribute more C [67], dominate most ecosystems, particularly in cropland [67,68], and are strongly influenced by edaphic conditions (e.g., total N, organic C, soil pH) and climate variables [55].

In this study, the observations reflect the effect of ecological zones as controlled by climatic variables, such as rainfall and temperature, which also control SOC contents. Rainfall and temperature directly relate to higher SOC but indirectly relate to low SOC contents [37,56–58]. The SOC directly affects basal respiration (Table 3) and contains POXC of about 4% of SOC [59]. POXC is the active fraction of SOC that is indispensable in soil ecosystems because it is an edaphic energy resource for the soil biological chain that drives the microbial community structure [61]. It, therefore, shows a high sensitivity to changes or perturbations in the environment and is thus considered an early indicator of C change in soils [59,60], although some studies did not find POXC sensitivity to change [58,69]. The POXC fraction in the SOC is influenced by soil conditions [58], such as clay mineralogy, and is usually high in kaolinitic soils and higher in smectitic soils because of their interactions [70], tillage or cultivation [58,60], long-term mineral fertilizer applications [71], texture [69], organic amendments [69], and soil pH [72]. Some of these influencing factors were found in this study at different levels. At the wide agroecology level, POXC was weakly, moderately, and strongly influenced by a number of other soil properties, which were mostly not significant (Table 3). While only ECEC and SEB had strong positive influences on POXC, Fe_d had a strong negative influence (Table 3). These

can also be the reasons for the relatively high %POXC/SOC in the Adansam soils, where the pH is relatively high, contents of pedogenic compounds [40] are present, and there is intense cultivation and mineral fertilizer application compared to the Dompem soils.

The findings of the two stages of this study reflect the effects of soil conditions on microbial indices. This has been confirmed by many authors [66,73,74]. However, the soil factors do not operate in isolation but interact with the effect of plant species or vegetation and the prevailing environment [22,38,75]. Consequently, Tosi et al. [41] found that the plant species effect explained 18.1% and 13.3% of the variance in bacterial and fungal species, respectively, against the effect of soil type, which was 47.1% for bacteria and 29.2% for fungi. These effects of vegetation and soil properties appear to operate both directly and indirectly, but it seems that the effects of vegetation on soil properties precede their effects on microbial properties [76]. Among the soil properties often quoted as controllers of soil microbial indices are soil pH [7,55,66,73,77], followed by SOC, soil texture, mineralogy [7,70,77], soil water content, nutrients, litter mass, available phosphorus, temperature, and sand and clay contents [43,76,78]. The levels of interaction exhibit both lateral and vertical spatial variability [78]. Furthermore, each of the soil properties interacts with the microbial properties at different spectra, producing unique impacts. For instance, soil pH was the strongest predictor of bacterial alpha diversity, which appeared more pronounced toward neutral pH [76]. These vegetation–soil–climate dynamics are responsible for the differences in microbial properties found in this study and those of Wobeng et al. [43] in Western Highlands and High Guinean savanna ecological zones of Cameroun and Tripathi et al. [76] in the mixed dipterocarp forest, heath forest, and peat swamp forest of Brunei.

5. Conclusions

The results of the two stages of the study confirmed our hypothesis that agricultural expansion tends to exert different pressures on the aboveground and belowground ecosystem in different cropping patterns, soils and soil management regimes, and agro-ecological zones. Whereas the first stage gave a pattern of the unique characteristics of each agro-ecological zone, the second stage further displayed intra-ecozone uniqueness in the different farm types. Generally, it is observed that the mineral soil and microbial properties of the farm types of sandy and less humid forest–savanna transition zone soils did not respond to cultivation in the same manner as the loamy soils of the forest zone. The observations are attributed to distinctive effects of vegetation and soil properties, which appear to operate both directly and indirectly with the effects of vegetation on soil properties, seemingly preceding those on microbial properties. The results suggest that an understanding of the magnitude, direction, and dynamics of these factors is essential for sustainable soil management in the future. Different crops affect microbial indices differently because of their contributions to the rhizosphere and the quality of plant residue returned to the soil. As the soil is the immediate home of the major drivers for providing ecosystem services in soils, it is imperative to pay more attention to conditions that prevail in the soils. However, too much focus on soils and crop yields alone may produce unwanted effects on soil biodiversity. This implies that, in some cases, there must be a compromise between soil conditions that support plant growth and good yields and those that promote healthy microbial diversity for sustained benefits. Arable soil management should follow the principle of financial accounts management, whereby a minimum balance is retained to sustain soil functions. This “minimum balance of soil health” is site-specific or ecozone-specific. This calls for research that seeks to achieve this in different spectra of soil, vegetation, and agro-ecological conditions.

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