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Duration of Cultivation Has Varied Impacts on Soil Charge Properties in Different Agro-Ecological Zones of Ghana

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Abstract: Agricultural expansion into natural habitats causes soil fertility decline after a period of cultivation. This study investigated changes in soil exchange properties in different farm types at Dompem and Adansam in the Forest and Forest–Savannah transition zones of Ghana as influenced by the duration of cultivation. Sixty farms were selected for soil sampling through a reconnaissance survey. The soils were subjected to physicochemical analysis. The results showed that the Dompem soils were loamic, had more amorphous Fe and Al oxides, were strongly acidic and had low contents of exchangeable acidity, a low sum of exchangeable bases (SEB), low effective cation exchangeable capacities (ECECs) and low available P. Conversely, the Adansam soils were arenic, slightly acidic and had relatively higher SEBs and ECECs. Interestingly, soil organic carbon (SOC) in the Dompem soils declined by >10% in relation to the duration of cultivation and showed rapid reductions within three years. Correspondingly, soil bulk density, CEC and SEB declined. In Adansam soils, only δpH declined in relation to the duration of cultivation. Soil organic carbon accounted for >50% of the ECEC and 49% of the SEB in Dompem soils but 36% of δpH in the Adansam soils. In conclusion, agricultural expansion, manifested in the duration of cultivation, mainly influenced soil charge properties through SOC decline.

Keywords: native vegetation; fallow; soil degradation; effective cation exchange capacity; pedogenic compounds; Delta pH

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1. Introduction

Agricultural expansion is known to produce impacts, synergies and tradeoffs [1–4]. In most cases, the impacts lead to declines in the ecosystem services provided by soils [1,5,6]. Provisioning and supporting services are crucial in sustaining the rest of the services. It is estimated that, in the coming decades, Sub-Saharan Africa (SSA) and South America will be the epicentres of agricultural expansion [1,7], which is expected to occur more rapidly than previously [1]. Incidentally, these areas also have soils that are most vulnerable to degradation due to the prevailing climatic conditions and specific soil types. When agricultural expansion continues under limited nutrient replenishment and improper nutrient balances, soils became prone to degradation, although other practices, such as inappropriate use of pesticides and tillage, can also cause soil degradation. Soil degradation refers to either the loss of or reduction in soil quality as a result of physical, chemical and biological processes [8] manifested as soil fertility or productivity decline. It is often associated with the depletion of the stored inherent fertility created by natural ecosystems.

Soil degradation is the force that compels farmers to encroach on uncultivated natural habitats, which have relatively superior soil quality. This ancient phenomenon drove the ancient shifting cultivation system and now manifests as land rotation systems, which currently dominate SSA agricultural systems. In a systemic review of drivers and constraints on agricultural expansion [3], soil fertility decline was found to be a direct driver of agricultural expansion into natural habitats. It was further described as a "more troubling trend", along with climate change and variability. It is estimated that in the 1980s and 1990s, over 60% and 35% of fresh farmlands were obtained from undisturbed and disturbed forests, respectively [7]. This suggests that more forests were cleared within that decade. Soil degradation is a vicious cycle in SSA agriculture, and a major threat to farmers' livelihoods [9], food security [10] and biodiversity and a barrier to poverty alleviation. In cases where there are limited natural habitats for agricultural expansion, limited mineral fertilizer use coupled with climate variability can create huge yield gaps. Yield gap assessments have shown that, soil fertility alone accounts for 69%, whereas soil type accounts for 58%, of existing yield gap records [11].

Agricultural expansion is a type of land-use change with impacts that can also be felt in different magnitudes and dimensions [6,12,13]. Earlier research has consistently shown that these impacts vary in taking the forms of nutrient inputs and their effects on aquatic ecosystems [14], changes in the quality of land [4], reductions in biodiversity and carbon storage [5,15] and changes in SOM fractions [6] among others. It has been established that soil organic matter (SOM) content declines after land clearing and in relation to duration of cultivation [6,16,17]. It is more pronounced when natural habitats are converted to agricultural lands. However, it tends to occur at varying rates and is accompanied by decreases in related soil properties with different trends [16,17].

In agroecosystems, the soil quality is influenced by the states of different croplands owing to crop nutrient requirements and uptake [18,19], cropping patterns or cropping history [20,21], years of cultivation since land clearing and decline in SOM content [17,22]. It is estimated that about 40–70% of native SOM—i.e., carbon (C) and nitrogen (N)—are lost after 50 years of cultivation, and this loss can be very devastating in sandy soils [20,21] which are more porous and prone to higher SOM decomposition [14]. Most of these soils are found in the forest–savanna transition ecological zone in the tropics. Blécourt et al. [23] reported an increase in agricultural expansion by 24% between 2002 and 2013, which caused a reduction in SOC and total N content in the soil in northeast Namibia and southwest Zambia. It was observed that, while chemical properties decline steadily in relation to the duration of cultivation, biological properties decline rapidly, reaching a steady state [17]. These are linked to the mineral composition, the nature and extent of degradation in the quality of SOM [22] and the general resilience of the soil ecosystem [24].

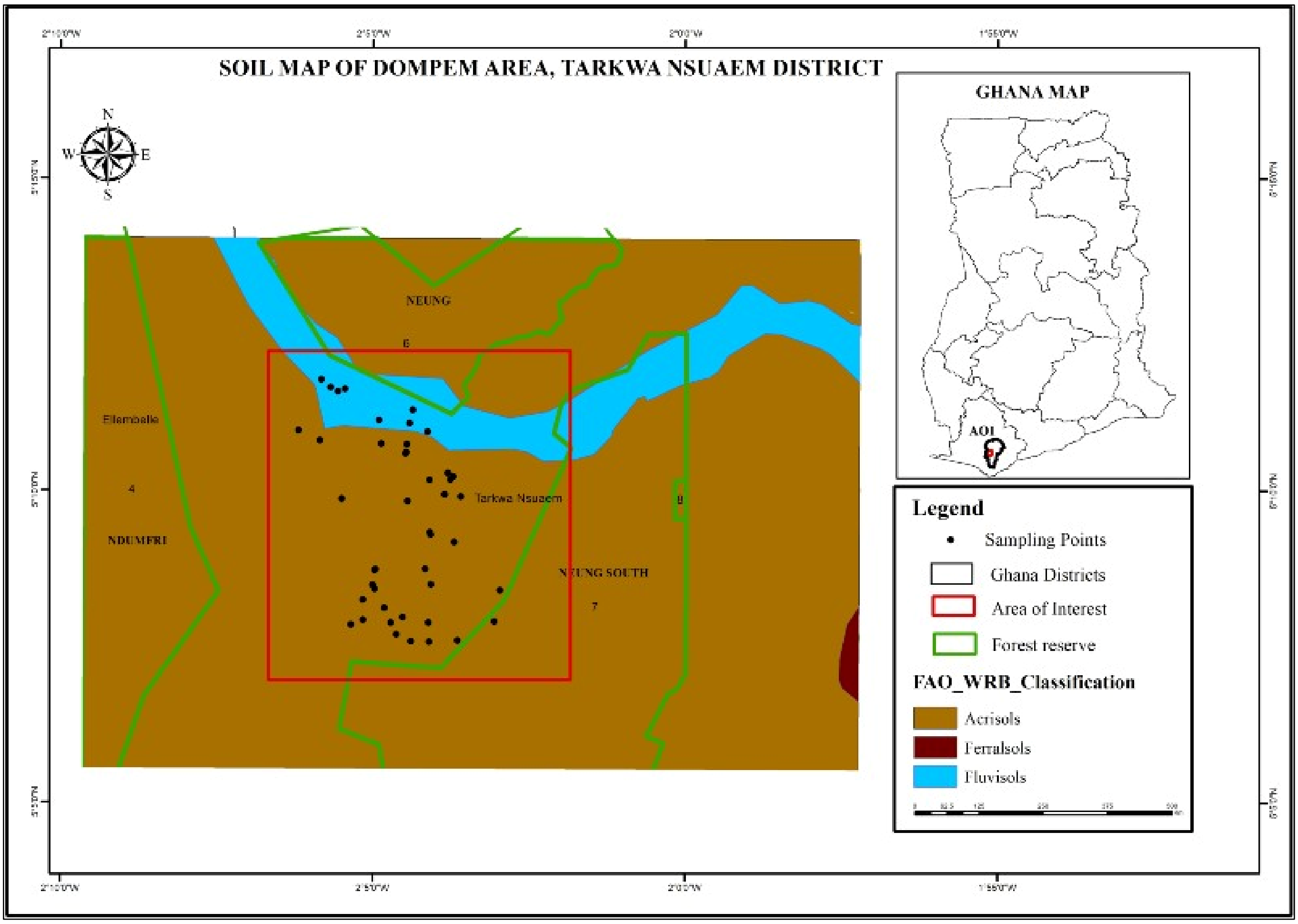
Soil organic matter is a "magic substance" because of its extensive influence on many soil properties, such as soil exchange properties. Some of these properties include exchangeable acidity, cation and anion exchange. These properties are essential and form the centre of nutrient retention and exchange processes in soils. They influence interactions between minerals and organic fractions, leaching, dispersion, flocculation, swelling and shrinking (Zhang and Zhao, 1997 cited in Moghimi et al.) [25]. It has been hypothesized that, due to the nature of land use and land-use in agricultural expansion, the rate of change in soil properties after conversion of forest to cropland differs in relation to the duration of cultivation [17] as more areas are cleared over a period of time. This study sought to investigate the changes in the soil exchange properties of different farms based on the duration of cultivation in the forest and forest–savannah transition zones of Ghana as influenced by agricultural expansion.

2. Materials and Methods

2.1. Site Description

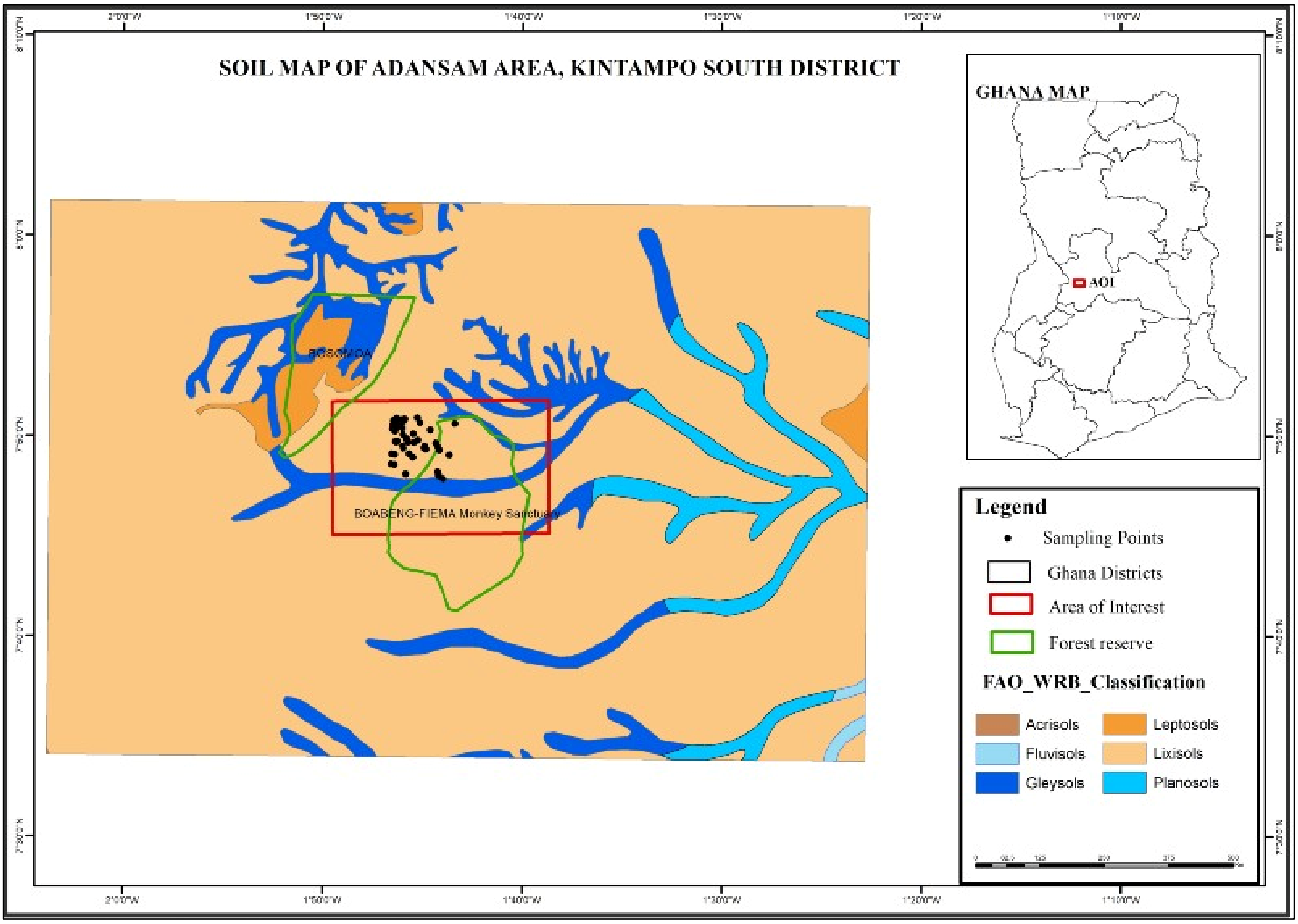
The study was conducted in the Dompem–Pepesa area (5°09′33.7″ N; 2°04′29.4″ W) located in the Tarkwa–Nsuaem Municipality in the forest zone (Figure 1a) and the Adansam–Kokuma area (7°50′35.9″ N 1°45′59.9″ W) within the Kintampo South District in the Forest–savannah Transition zone of Ghana (Figure 1b). The geology of the Dompem site is dominantly Birrimian, Tarkwaian and, to a less extent, granite, comprising granites, sandstones, phyllites and conglomerates. In contrast, the Adansam site is located on the Voltaian system, comprising mudstone, sandstone, conglomerates, tillites and limestone [26]. These sites were selected after a reconnaissance survey of six sites selected across the country under the Sentinel Project (Social and Environmental Trade-offs in African Agriculture). The criteria used to identify the sites were:

1. Proximity to natural habitats with low levels of degradation, still provides a range of ecosystem services, and has the potential for agricultural expansion into those areas;
2. Evidence of agricultural expansion; i.e., increase in the area under agricultural land use of any type;
3. Expansion is partially driven food by crop production and is largely dominated by smallholder farmers;
4. Easy access to road networks or settlements;
5. Willingness of communities to work with the project team; and
6. Exhibits a contrast in terms of the agro-ecological zone and the natural habitat that is lost to agriculture within an approximately 10–20 km^2 area.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. The study area showing sampled locations (black dots) at (**a**) Dompem in the Forest zone and (**b**) Adansam in the Forest-Savannah Transition zone.

At each location, farmers from both genders were categorized using local wealth rankings obtained during the reconnaissance survey; for example, wealthy, moderately wealthy and poor. The major indicators of wealth were farm size, type of house, number of houses, furniture type, disposable income, availability of food in the house, diversity of diet, number of meals per day, diverse livelihood options, means of transport and ability to hire farm labour. The aim of including wealth ranks was to find out if farmer's resources play a role in soil management. Sixty (60) farmers from each zone, with twenty (20) farmers from each wealth category, were interviewed, followed by sampling from their farms. For each wealth category, farms were selected by considering farms located near and around neighbouring forests or natural habitats and farms located elsewhere within the area that fell into the five farm types stated above. The target farm types were confirmed during participatory transect walks (Table 1). "Forest" in this context refers to the natural habitats found in the ecological zones whereas "Fallow" refers to plots that had been cultivated and left to regain fertility for a few years before the next round of cultivation. Soil sampling was undertaken between May and July 2021 during the early part of the rainy season.

Table 1. Farm types, corresponding wealth rankings and numbers of farms per wealth ranking and farm type.

Farm Types	Very Wealthy	Moderately Wealthy	Poor	Total
First cultivation of native vegetation (year one)	4	4	4	12
First cultivation of fallow land (year one)	4	4	4	12
Three years of cultivation	4	4	4	12
Five years of cultivation	4	4	4	12
Ten years of cultivation	4	4	4	12
Grand total	20	20	20	60

Note: The farm ages are the upper limits (e.g., up to three years, etc.).

Over 80% of farms at the Dompem–Pepesa area were located on brown sedentary, moderately well-drained Ferric Acrisols (Yakasi series), while the rest were imperfectly drained, alluvial clay Eutric Fluvisols (Kakum series), which occur in association with drained, loose alluvial Gleyic Arenosols (Chichiwere series). The crops grown were cassava (*Manihot esculenta* Crantz), plantain (*Musa paradisiaca* L.), maize (*Zea mays* L.), cocoyam (*Xanthosoma* spp.), rice (*Oryza sativa*), tomatoes (*Solanum lycopersicum* L.), okro (*Abelmoschus esculentus* (L.) Moench) and pepper (*Capsicum* sp. L.). The farms of the Adansam–Kokuma area were located within the Damongo–Murugu association and comprised Ferric Luvisols (Damongo series), Haplic Luvisols (Murugu Series) and Dystric Gleysols (Tanoso series). The Ferric Luvisols were located on the upper slopes and were very deep, non-gravelly, red, well-drained, fine sandy loams or clay loams. The Haplic Luvisols were located on the middle slopes and were very deep, non-gravelly, yellowish red, moderately well-drained, sandy loams, while the Dystric Gleysols valley-bottom soils were very deep to deep, poorly drained, very loose loamy sands. The crops grown in the area were dominantly yam (*Dioscorea* sp.), maize, groundnut (*Arachis hypogaea* L.), cassava, okro, pepper and garden eggs (*Solanum melongena* L.), in decreasing order of prevalence. The soil classification was undertaken by the Soil Research Institute of the Council for Scientific and Industrial Research (CSIR) according to the IUSS Working Group WRB [27].

2.2. Sampling and Laboratory Analysis

Soil sampling was conducted between May and July 2021 during the early part of the rainy season. Five samples, including core samples for bulk density, were randomly collected from each farm at up to 20 cm depths. The samples were composited, air-dried, filtered through a 2 mm sieve and prepared for laboratory analysis. The air-dried samples were subjected to standard laboratory analyses at the Department of Soil Science, University of Ghana, and at the Soil Research Institute of the Council for Scientific and Industrial Research. The bulk density and particle size distribution were determined using the core method [28] and the Bouyoucos hydrometer method, as modified by Day [29], respectively. The soil pH (in water and KCl) was measured using a soil–solution ratio of 1:2.5 [30] with an OAKTON PC 2700 benchtop meter. The exchangeable bases were extracted with ammonium acetate buffered to pH 7 [31] and measured with an atomic absorption spectrometer (AAS) (NovAA 400 P, Analytik Jena GmbH, Germany). The effective cation exchange capacity (ECEC) was calculated by summing the exchangeable bases and exchangeable acidity. The available P was measured using the Bray 1 method [32] on a Shimadzu UV 1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan). Total carbon (i.e., SOC, since no carbonates were present in the soil) and nitrogen were measured by dry combustion of 0.15 g of soil filtered through a 0.5 mm sieve on a LECO Corporation TruMac Series CNS—2000 Analyzer (Leco Corporation, St. Joseph, MI, USA). The pedogenic minerals (dithionite-citrate-bicarbonate-extractable Al and Fe) were determined using the method described by Mehra and Jackson [33] and Schwertmann [34] and measured using the AAS.

2.3. Statistical Analyses

It was not possible to obtain all the farm types in each wealth category and, thus, the target population. This defeated the aim of including wealth rank as a factor. Furthermore, an initial exploration of the data did not show any significant influence of wealth ranks on soil properties. Therefore, only the farm types linked with the duration of cultivation were considered for the statistical analyses. To extract the appropriate data for statistical analysis, the data, starting with the SOC content, were checked for consistency in each farm type, and outliers were removed where necessary. Consequently, 9 farm replicates were obtained for Dompem, whereas 11 were obtained for Adansam. All the data were checked for conformity to analysis of variance (ANOVA), bivariate correlation and multiple linear regression. Where necessary, non-normal data were log- or square-root-transformed. The data were assessed to examine whether the duration of cultivation had significant impacts on the soil properties using one-way ANOVA, and the means were compared using Tukey HSD tests. In the case of non-normal data, non-parametric statistical analyses, such as Kruskal–Wallis/Mann–Whitney U tests and Spearman's correlation, were applied. Multiple regression models were run to identify the predictors of charge properties using the stepwise forward method in SPSS version 20 (IBM, New York, NY, USA). All regression models were tested for normality, constancy of variance, absence of correlation between the residuals (Durban–Watson statistics) and absence of multi-collinearity, calculating the variance inflation factor (VIF). Pearson's and Spearman's correlations were conducted for normal and non-normal data. The graphs were created using Sigma Plot 12.

3. Results

3.1. Basic Properties of the Soils

The properties of soils are a reflection of their inherent nature. The Dompem soils were dominantly Gleyic Acrisols and Arenosols with sandy loam textures (16–31% silt + clay), whereas the Adansam soils were Ferric Luvisols, Haplic Luvisols and Dystric Gleysols with sandy (8.7–11% silt + clay) texture (Table 2). These textural classes were reflected in the bulk densities in each study site. Consequently, the Dompem soils had lower bulk densities of ($\leq$1.3 g cm^{-3}) and differed (p = 0.013) among the farm types compared to the Adansam soils (Table 2). The clay content of the Dompem soils correlated positively with the delta pH (δpH) (r = 0.50, $p < 0.01$), ECEC (r = 0.45, $p < 0.01$), SEB (r = 0.73, $p < 0.001$) and SOC (r = 0.66, $p < 0.001$) values but correlated negatively with the Al_d (r = −0.46, $p < 0.01$) (Table 4). Conversely, the clay content of the Adansam soils negatively correlated with soil pH (r = −0.51, $p < 0.001$) and available p (r = −0.72, $p < 0.001$) but positively correlated with exchangeable acidity (r = 0.30, $p < 0.05$), ECEC (r = 0.58, $p < 0.001$), SEB (r = 0.58, $p < 0.001$), SOC (r = 0.39, $p < 0.01$) and Fe_{ox} (r = 0.51, $p < 0.001$) (Table 5). The δpH negatively correlated with Ald (r = −0.33, $p < 0.05$), Fed (r = −0.43, $p < 0.01$), SOC (r = −0.58, $p < 0.001$) but positively correlated with available p (r = 0.34, $p < 0.05$) (Table 5).

The pH_{water} for the Dompem soils (4.2 to 4.6) was about two pH units lower than those of Adansam (6.3 to 6.5) but did not differ ($p > 0.050$) among the farm types (Table 2). Soil pH correlated negatively with δpH (r = −0.44, $p < 0.01$) and exchangeable acidity (r = −0.70, $p < 0.001$) (Table 4). The δpH, defined by the difference between the pH values measured in KCl and water, was negative (−0.4 to −0.6) for all the Dompem soils and differed (p = 0.023) among the farm types. Unlike the Dompem soils, the Adansam soils had both negative and positive δpH values (0.2 to −0.4), showing significant differences (p = 0.003) among the farm types. They correlated positively with ECEC (r = 0.45, $p < 0.01$). The exchangeable acidity of the Dompem soils (0.1 to 2.3 $cmol_c$ kg^{-1}) was higher than those of the Adansam soils and differed (p = 0.030) among the farm types. The Dompem soils had only 40 to 60% of the SEB in the Adansam soils, although there were no significant differences ($p > 0.050$) among the farm types of each study site. Again, the Dompem soils had only 40 to 90% of the ECEC in the Adansam soils and significantly differed ($p < 0.001$) among the farm types compared to those of Adansam (Table 2).

Table 2. Soil bulk density, particle size distribution, soil pH (water and KCl), delta pH, exchangeable acidity, sum of exchangeable bases and the effective cation exchange capacity (ECEC) of soils from different farm types in Dompem (n = 9) and Adansam (n = 11) with coefficients of variation and p-values.

Farm Type	Bulk Density (g cm^{-3})	Sand	Silt	Clay	Textural Class	Soil pH		Delta pH	Exch. Acidity	SEB	ECEC
		%				Water	KCl		cmol$_c$ kg^{-1}		
Dompem											
Year one	1.04 a	68.9 a	20.3 a	10.9	Sandy loam	4.17	3.72	−0.5 a	2.7 a	3.9	6.6 a
Three years	1.15 b	71.3 a	17.2 b	11.4	Sandy loam	4.36	3.97	−0.4 b	0.9 b	3.7	4.7 b
Five years	1.24 c	76.4 a	15.1 c	8.4	Loamy sand	4.53	4.03	−0.5 c	0.8 b	3.5	4.4 b
Ten years	1.27 d	84.0 b	9.3 d	6.7	Sand	4.61	4.00	−0.6 d	0.5 c	2.6	3.1 c
CV (%)	99.9	101.4	95.6	96.3	-	100.5	100.3	102.2	92.5	100.7	98.5
***p*-value**	0.009	0.036	0.014	0.111	-	0.133	0.333	0.023	0.030	0.199	<0.001
Adansam											
Year one	1.33	90.2	3.3	6.5	Sand	6.40	5.96	−0.4 a	0.4	6.9	7.3
Three years	1.34	89.1	2.2	8.7	Sand	6.30	6.35	0.0 b	0.3	6.6	6.9
Five years	1.41	91.4	2.4	6.3	Sand	6.40	6.56	0.2 c	0.4	7.9	8.2
Ten years	1.36	89.6	2.2	8.2	Sand	6.46	6.59	0.1 d	0.4	6.6	7.0
CV (%)	6.5	5.2	57.6	54.1	-	7.0	10.4	-	17.9	53.2	50.8
***p*-value**	0.118	0.735	0.393	0.277	-	0.985	0.052	0.003	0.178	0.348	0.116

The listed textures also corresponded to the textures that dominated each farm type. Means followed by different lowercase letter(s) in the columns are significantly different.

Further, the analysis of pedogenic Al and Fe showed that the soils of both study sites were dominated by Fe (Fe_d and Fe_{ox}) (Table 3). The Fe_d contents of Dompem were 4 to 16 times higher than those of Adansam soils but did not differ significantly among the farm types ($p > 0.05$). Those of Adansam soils differed significantly ($p < 0.001$) among the farm types (Table 3). The Fe_{ox} contents of Dompem were one- to fivefold those of the Adansam soils, showing significant differences ($p < 0.001$) among the farm types. The Al_d was one- to threefold higher than Al_{ox}, whereas Fe_{ox} was generally high for both study sites, yielding an active ratio of 5 to 36. The crystalline Al and Fe contents (Al_d and Fe_d) for the Dompem soils showed diverse relationships with other soil properties. For instance, they correlated negatively with each other (r = −0.46, $p < 0.01$), clay (r = −0.46, $p < 0.001$), ECEC (r = −0.72, $p < 0.001$), SEB (r = −0.63, $p < 0.05$) and Al_{ox} (r = −0.63, $p < 0.01$) (Figure 2a) but positively with SOC (r = 0.36, $p < 0.05$), exchangeable acidity (r = 0.49, $p < 0.01$) and ECEC (r = 0.38, $p < 0.05$, Table 4; r = 0.44, $p < 0.01$, Figure 2b). For the Adansam soils, Al_d and Fe_d were only negatively correlated with δpH (r = −0.33, $p < 0.05$; r = −0.43, $p < 0.01$) (Table 5), and Al_{ox} was negatively correlated with ECEC (r = −0.33, $p < 0.05$), SEB (r = −0.35, $p < 0.05$) and Al_d (r = −0.55, $p < 0.01$). Oxalate Fe was positively correlated with clay content (r = 0.51, $p < 0.001$) and exchangeable acidity (r = 0.41, $p < 0.01$). Finally, the Dompem soils had one- to threefold more SOC than the Adansam soils and showed significant differences ($p < 0.001$) among the farm types (Figure 3). The available P content of the Dompem soils was about 20 to 60% of that in the Adansam soils but did not differ ($p > 0.050$) among the farm types in either study site (Figure 4).

Table 3. Pedogenic Al and Fe contents and the active Fe ratio in soils of different farm types from Dompem (n = 9) and Adansam (n = 11) with coefficients of variation and p-values.

Farm Type	Al_{ox}	Al_d	Fe_{ox}	Fe_d	Fe_{ox}/Fe_d
	mg kg^{-1}		mg kg^{-1}		
Dompem					
Year one	23.8 a	25.9 a	1889.1a	568.0	6.6
Three years	18.0 b	34.6 b	2249.0 b	229.5	18.9
Five years	22.3 a	28.8 c	1293.2 c	258.4	5.3
Ten years	20.0 a	35.1 d	686.7 d	274.1	7.5

Table 3. *Cont.*

Farm Type	Al_{ox}	Al_d	Fe_{ox}	Fe_d	Fe_{ox}/Fe_d
	mg kg^{-1}		mg kg^{-1}		
CV (%)	98.9	100.7	99.0	92.6	102.2
***p*-value**	0.003	<0.001	<0.001	0.063	0.192
Adansam					
Year one	13.9 a	39.4 a	489.7	43.6 a	14.9 a
Three years	15.8 b	28.7 b	432.9	57.9 a	8.3 b
Five years	16.5 c	24.9 c	563.4	16.0 b	35.9 c
Ten years	16.3 c	25.0 c d	502.3	29.5 a	25.5 d
CV (%)	11.2	22	35.8	60.0	78.8
***p*-value**	0.003	<0.001	0.540	<0.001	<0.001

Means followed by different lower-case letter(s) in the columns are significantly different.

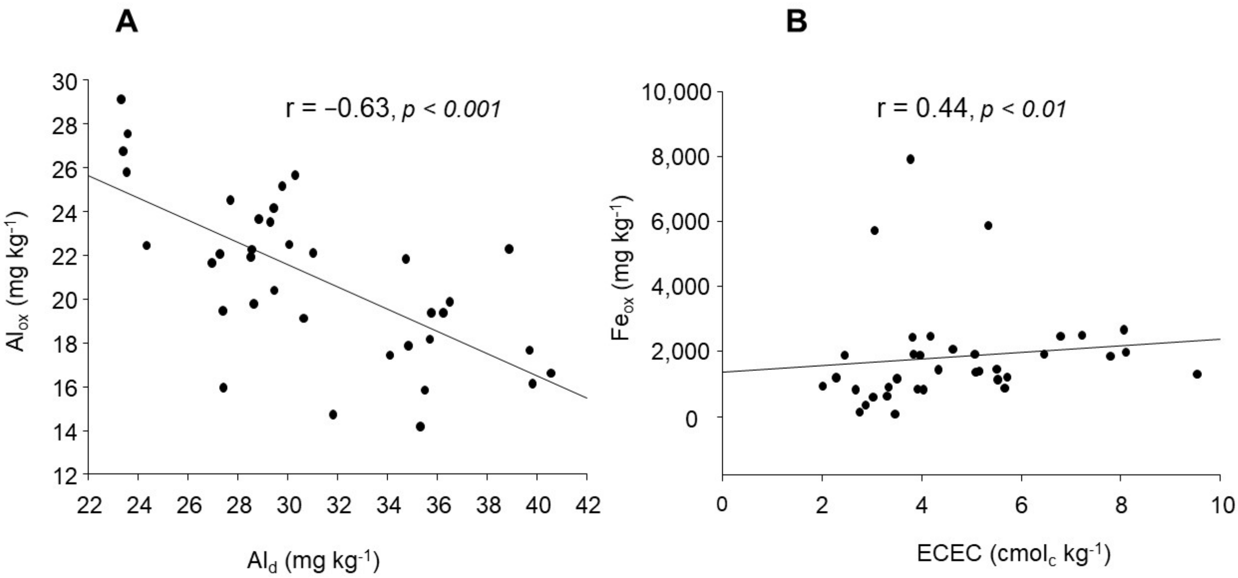


Figure 2. Correlations showing (**A**) a positive correlation between Al_d and Al_{ox} and (**B**) a negative correlation between Fe_{ox} and ECEC for the Dompem soils.

Table 4. Pearson and Spearman correlation coefficients for the Dompem soils.

	Clay	pH	δpH	EA	ECEC	SEB	Al_d	Fe_d	SOC
Clay	1								
pH	−0.30	1							
δpH	0.5 **	−0.44 **	1						
EA	0.29	−0.7 ***	0.14	1					
ECEC	0.45 **	−0.30	0.45 **	0.33 *	1				
SEB	0.73 ***	0.27	0.32	−0.33	0.65 ***	1			
Al_d	−0.46 **	0.38 *	−0.21	−0.35 *	−0.72 ***	−0.63 *	1		
Fe_d	0.36 *	−0.14	−0.06	0.49 **	0.38 *	−0.06	−0.46 **	1	
SOC	0.66 ***	−0.11	0.35*	0.2	0.83 ***	0.66 ***	−0.64 ***	0.36 *	1

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; Al_{ox} and Fe_{ox} had only one significant correlation each, while the available P had no significant correlations with other soil properties, so it was removed.

Table 5. Pearson and Spearman correlation coefficients for the Adansam soils.

	Clay	**δpH**	**EA**	**ECEC**	**SEB**	**Al$_d$**	**Al$_{ox}$**	**Fe$_{ox}$**	**SOC**	**Avail. P**
Clay	1									
pH	−0.51 ***									
δpH	−0.27	1								
EA	0.30 *	−0.06	1							
ECEC	0.58 ***	−0.22	0.25 *	1						
SEB	0.58 ***	−0.22	0.29	1.0 ***	1					
Al$_d$	−0.13	−0.33 *	−0.11	0.04	0.05	1				
Fe$_d$	0.22	−0.43 **	−0.21	0.09	0.11	0.42 **				
Al$_{ox}$	−0.18	0.28	0.03	−0.33 *	−0.35 *	−0.55 **	1			
Fe$_{ox}$	0.51 ***	−0.12	0.41 **	0.26	0.25	−0.11	−0.21	1		
SOC	0.39 **	−0.58 ***	0.13	0.57 ***	0.58 ***	0.14	0.38 *	0.30 *	1	
Avail. P	−0.72 ***	0.34 *	−0.22 *	−0.44 **	−0.44 **	−0.07	0.13	−0.39 *	−0.25	1

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; Soil pH and Fe$_d$ had no significant correlations with other soil properties so they were removed.

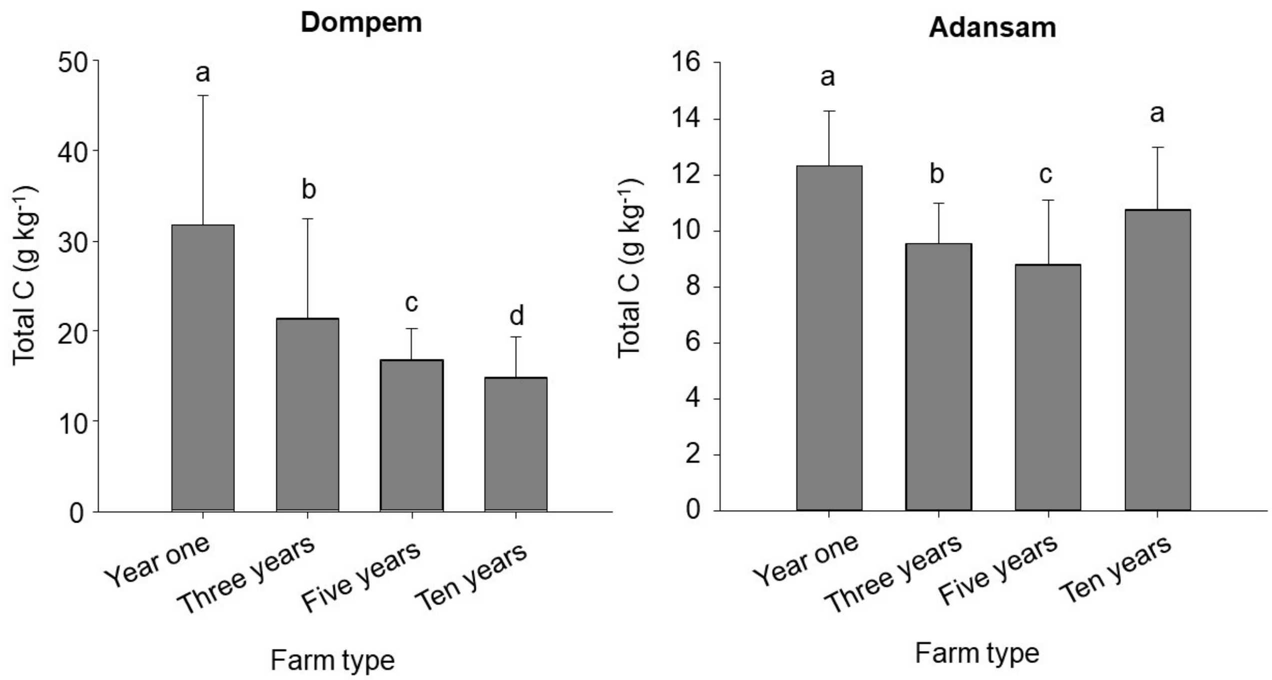


Figure 3. Mean total carbon content of soils from Dompem (p = 0.001) and Adansam (p = 0.001) (n = 9 + one Standard deviation) and Adansam (n = 11 ± one Standard deviation).

3.2. Soil Properties Affected by the Duration of Cultivation

It was discovered that the duration of cultivation affected some soil properties, particularly in the Dompem soils. For instance, the mean bulk density increased by 0.11, 0.09 and 0.03 g cm^{-3} in years one, three and five, respectively. Conversely, the SOC content decreased in relation to the duration of cultivation by margins of 17, 16 and 15% among the farm types (Figure 3), yielding a strong negative correlation (r = −0.52, p = 0.001) with the soil bulk density (Figure 5). Further, the mean pH of the Dompem soils increased by ≥0.1 pH units in relation to the duration of cultivation from year three onwards but remained < 5 (Table 2). Dompem soil pH had a moderate negative correlation with δpH (r = −0.44, p < 0.01) and a strong negative correlation with exchangeable acidity (r = −0.70, p < 0.001) (Table 4). By contrast, the exchangeable acidity decreased by 1.8, 0.1 and 0.3 cmol$_c$ kg^{-1} from years one, three and five, respectively. Correspondingly, the ECEC decreased by 1.9, 0.3 and 1.3 cmol$_c$ kg^{-1} at years one, three and five, respectively. The decreases in exchangeable acidity and ECEC were steeper between years one and three, steady between the third and fifth years and steeper again between years five and ten. The exchangeable acidity had a moderate positive correlation with Fe_d (r = 0.49, $p < 0.01$) and a strong negative correlation with soil pH (r = −0.70, $p < 0.001$). The ECEC had a strong positive correlations with SEB (r = 0.65, $p < 0.001$), SOC (r = 0.83, $p < 0.001$) and clay content (r = 0.45, $p < 0.01$) but a strong negative correlation with Al_d (r = −0.72, $p < 0.001$). Unlike the Dompem soils, only the δpH of the Adansam soils showed a decline (Table 2) in relation to the duration of cultivation, where it changed to zero and positive values. The steepest decline occurred between years one and three.

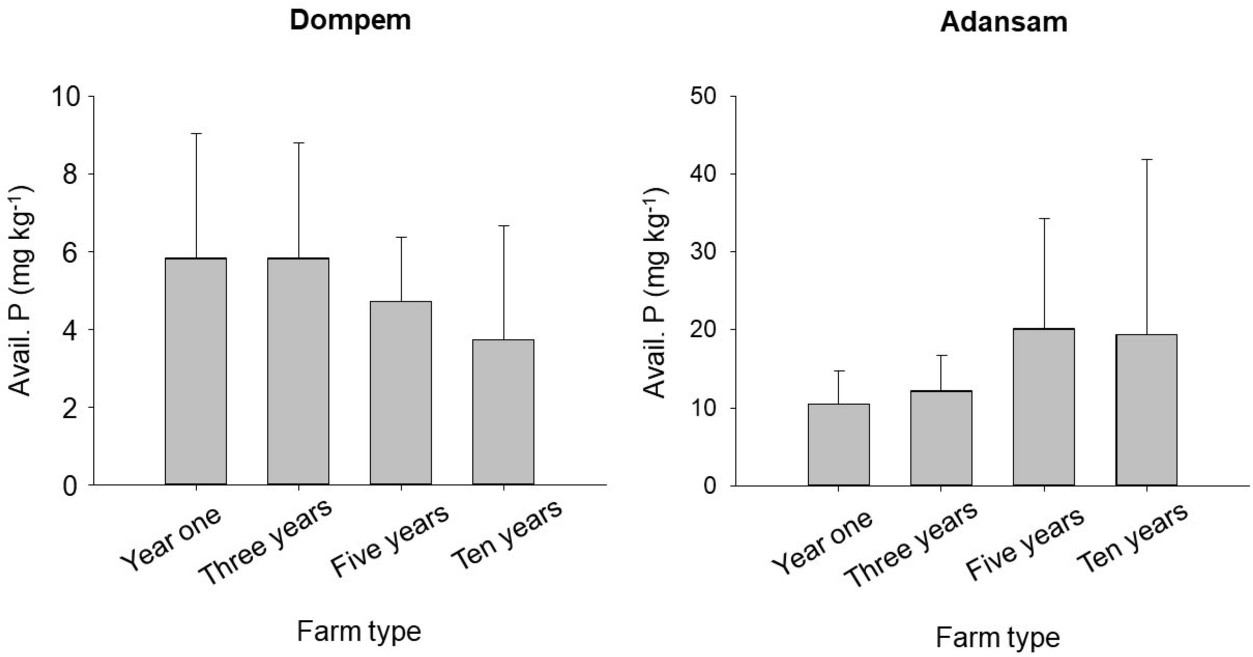


Figure 4. Available P contents in soils of Dompem ($p > 0.05$; $n = 9 \pm$ one standard deviation) and Adansam ($p > 0.05$; $n = 11 \pm$ one standard deviation).

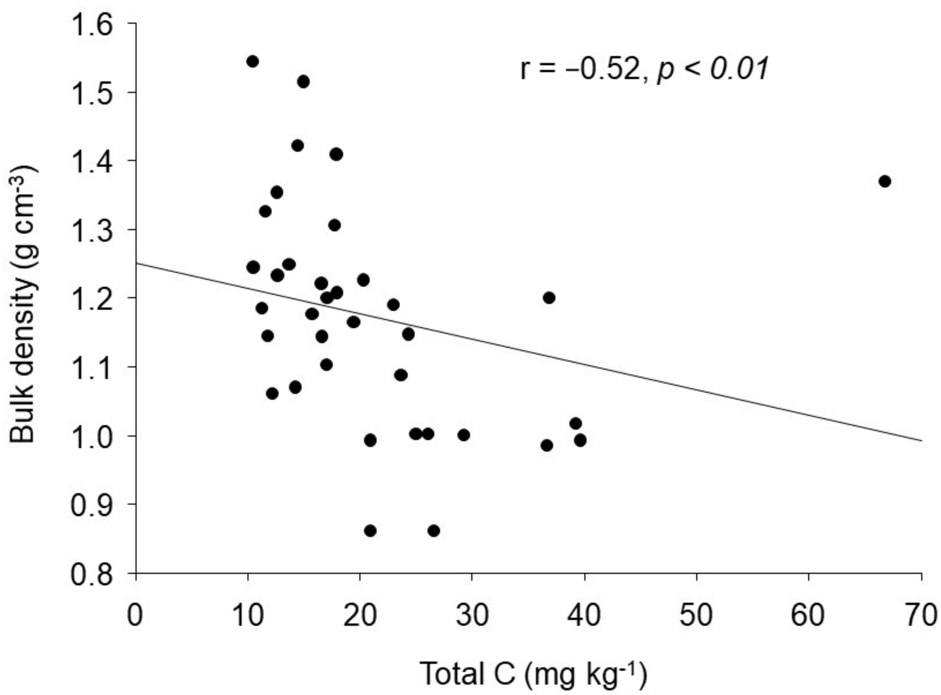


Figure 5. Spearman correlation between bulk density and SOC for Dompem soils.

The general observation is that the properties that were affected by years of cultivation were all related to charge development, dynamics, sorption and ion exchange in soils. Consequently, the multiple regression model revealed that SOC predicted most of the charge properties of the Dompem soils. For instance, SOC accounted for 56.2% of ECEC whereas Al_d, SEB and exchangeable acidity accounted for 17.3%, 19.6% and 4.1%, respectively, yielding a coefficient of determination of 97.2% ($p < 0.001$) (Table 6). Again, SOC accounted for 48.5% of SEB whereas ECEC, exchangeable acidity and Al_d accounted for 31.3%, 14.1% and 1.6%, respectively, producing a coefficient of determination of 95.5% ($p < 0.001$). For the Adansam soils, SOC predicted 36.3% of the δpH whereas the crystalline compounds (Al_d and Fe_d) accounted for 15.5% and 6.6%, respectively, producing a coefficient of determination of 58.4% ($p < 0.001$) of the δpH (Table 6). The SEB and exchangeable acidity accounted for 99.8% and 0.2% of the ECEC, respectively amounting to 100% ($p < 0.001$). Further, ECEC and exchangeable acidity accounted for 99.8% and 0.2% of the SEB with a coefficient of determination of 100% ($p < 0.001$).

Table 6. Multiple linear regression models (stepwise forward method) between charge properties and other soil properties for each study site.

Variable	Intercept	Predictor 1	Predictor 2	Predictor 3	Predictor 4	R^2 (%)
Dompem						
ECEC	0.646	−0.002SOC **	−0.008Al_d **	0.08EA **	0.091SEB **	97.2 ***
SEB	0.376	−0.003SOC **	−0.121EA **	0.116ECEC **	−0.007Al_d **	95.5 ***
Adansam						
ECEC	0.001	1.0SEB ***	0.997EA ***	-	-	100 ***
SEB	−0.001	1.0ECEC ***	−0.997 EA ***	-	-	100 ***
Delta pH	1.489 ***	−0.08SOC ***	−0.017Al_d ***	−0.005Fe_{ox} ***	-	58.4 ***

ECEC: effective cation exchange capacity; SEB: sum of basic cations; EA: exchangeable acidity; *** $p < 0.001$; ** $p < 0.01$.

4. Discussion

4.1. Basic Properties of the Soils

The properties of the soils from each study site were characteristic of the agroecological zones and the dominant soil types. The properties were both inherent and dynamic. For instance, the texture of Dompem soils could be described as loamic, in accordance with the IUSS Working Group WRB [27]. They were dominantly brown Ferric Acrisols, alluvial clay (Eutric Fluvisols) or, to a less extent, alluvial sands (Gleyic Arenosols). These soils contained significant amounts of amorphous Fe and Al oxides, as shown in the high Fe_{ox}/Fe_d ratios [35]. These high amounts of amorphous oxides were associated with the extent of weathering under the prevailing climatic and drainage conditions, as these tend to enhance the non-crystallinity of Al and Fe [36,37]. A visual assessment and colour determination showed that the soils had reddish brown, saprolitic yellowish and greyish colours, indicating the presence of amorphous minerals [38]. A considerable number of the Dompem soils had yellowish colours, characteristic of iron-rich saprolite [38]. Additionally, they contained some crystalline minerals, such as quartz, kaolinite, muscovite [39,40] and Goethite in association with hematite and gibbsite [39,41,42]. Consequently, the soils were highly acidic, with pH < 5.0, which is characteristic of Upper Birimian geology [43]. The pH values reflected the pK_a (acid dissociation constant) of Fe oxides ($pK_a = 3$) to a large extent and that of Al oxides to a limited extent, as seen in the weak correlation between pH (water) and Al_d ($r = 0.38$, $p < 0.05$) (Table 4). The soils had δpH values that were similar to those of Brazilian Ferralsols as found by Locatelli et al. [6]. These values appeared to have a weak relationship with SOC (Table 4). Further, the parent material and dominant pedogenic processes also created conditions for the prevailing physical (texture, bulk density) and some chemical (exchangeable acidity, SEB and ECEC) properties. Generally, these soil minerals tend to have high point of zero charge values [42,44]. Therefore, at the prevailing soil pH, positive charges dominated [45], leading to low CEC, high anion retention and low SEB (Table 2) and available P contents (Figure 4) in the soils. Similar textures and pH and δpH values were found in Brazilian Ferralsols [6]. The exchangeable acidity, SEB and ECEC values were similar to those found in Oxisols of the rainforest zone by Dwomo and Dedzoe [43]. They were, however, about 20–30% lower than those found in Acrisols, Lixisols and Luvisols of the neighbouring moist semi-deciduous forest zone of Ghana [43,46].

On the other hand, the Adansam soils were of alluvial origin and could be described as arenic soils [27], as reflected in the texture (Table 2). This translated into relative higher soil bulk density and pH. The pH values also resulted in low exchangeable acidity and substantial SEB and ECEC values. The geology, hydrology and climate also influenced the formation and presence of Al and Fe oxides, as seen in the lower contents compared to the Dompem soils (Table 2). As expected of sandy soils, the δpH was positive for most of the farms. This may be explained by the fact the area is underlain by the sedimentary Voltaian formation. This consists primarily of sandstone, shale, mudstones and limestone, which is inherently high in basic cations. The parent material also contains calcite, dolomite and other liming materials, which may have relatively high acid-neutralizing capacity and reactivity. These may have contributed to the positive δpH and significant SEB and ECEC values. Ng et al. [47] observed a significant improvement in soil pH, available P, SEB and ECEC when Calciprill, natural calcium carbonate and sodium silicate were used for soil leaching- and pH buffering-capacity studies due to their alkaline nature. In the same experiment, the acid-neutralizing effects of the treatments hindered the hydrolysis of Al^{3+}, Fe^{2+} and Mn^{2+} by 96.5%, 70.4% and 25.3%, respectively, which reduced the production of H^+ [47], as seen in the low exchangeable acidity compared to the Dompem soils (Table 2). The soils are predominantly Ferric Luvisols (Damongo series), which have an overlying finer-textured mineral horizon that has higher clay content than the overlying horizon and the Haplic Luvisols (Murugu Series). These translated into relatively high soil bulk density and pH. The pH values also resulted in low exchangeable acidity with substantial SEB and ECEC typical of Luvisols.

4.2. Soil Properties Affected by the Duration of Cultivation

Agricultural expansion, as defined by doubling in crop production due to increasing demands, is manifested in spatial increases in farm lands aimed at increasing productivity using relatively more fertile soils. During the field study, it was observed that most of the farmers who expanded their farmlands did so either by clearing additional portions within natural habitats or by moving out into entirely new natural habitats. From this moment onwards, cultivation continued until the soil fertility was exhausted. The land was then left fallow while new areas were cleared to continue the cycle. This system of cultivation has resulted in several types of impacts on the ecosystem services provided by the above- and belowground biodiversity. Aside from the basic properties of the soils of each study location, the results suggest that agricultural expansion, manifested by the duration of cultivation (farm types), has had impacts on certain soil properties.

The results presented two contrasting patterns associated with agricultural expansion in the agroecological zones. Two trends of decline could be observed in the rainforest soils of Dompem. First, the most conspicuous observation was the SOC decline of >10%, which occurred in accordance with the duration of cultivation (Figure 3). The steepest decline occurred within the first three years of cultivation. In previous studies several decades ago, a much higher fraction of 58% SOC was lost within seven years of continuous cultivation within in the forest zone of Nigeria (Adepetu, 1994 cited by Badejo) [48]. This was accompanied by a 53% decline in CEC and 25% decline in maize yield. Similarly, after five years of converting forests to agricultural land in Njala in the rainforest zone of Sierra Leone, Brams [49] observed a decline of 50% in the SOC and 30% in the CEC, which led to a decline in soil productivity. He also observed the steepest decline in SOC after three years of cultivation. Further, Adiku et al. [50] observed that the removal of residue from farm land in the forest–savannah zone without replacement reduced SOC by 61% within four years of maize cultivation. The SOC decline has been observed to be nonlinearly related to the duration of cultivation and to reach a steady state after several decades with a different quality from the original SOC [17,22,51]. Second, the decreases in the exchangeable acidity and the ECEC were the largest in the first three years. This occurred along with increases in soil pH by a slightly larger margin within the first five years (Table 2). This observation corroborates other studies that also observed rapid impacts in the earliest stages of agricultural expansion **[5,6,17]**. Soil pH and CEC are said to exhibit linear declines [17,22].

Aside from climatic effects, soil texture and mineralogy could have been the determinants of the observed trends in the SOC of the Dompem loamic soils, although we did not determine the mineralogy. However, soil mineralogy was the main determinant of the rate of carbon turnover in British, Kenyan and Zambian soils through organo-mineral interactions [52]. These are formed as a result of chemical bonds between SOM and mineral surfaces and are occluded within small aggregates of <50 to 63 µm [53]. The association is predominant in silt and clay fractions [53,54]. Poorly crystalline Fe and Al content predict SOC turnover [55,56] because organo-mineral associations tend to protect SOC against microbial access and decomposition [6,53], irrespective of the disturbance. These organo-mineral associations have been found to occupy over 80% of SOM [55], depending on the quality (low CN ratio, high soluble C) of organic material [6]. Soil texture and mineralogy may have accounted for the relatively higher SOC in the Dompem soils than in the Adansam soils (Figure 2). The SOC was a significant predictor of ECEC and SEB (Table 6). This has also been found in loamy soils by Ping et al. [57] and Gruba and Mulder [16] due to the huge contribution of SOC to exchange properties, in the range of 150–500 $\text{cmol}_c\ \text{kg}^{-1}$ depending on the pH [57–59]. For instance, in a Brazilian Alfisol, SOC was responsible for about 12 to 56% of ECEC at pH 7 [60], which suggests a higher ECEC value at lower pH levels. Considering the texture of the Adansam soils, only the δpH showed a decline related to the duration of cultivation, where the charge sign changed from negative to zero and positive (Table 2) and the largest decrease occurred within the first three years. Once again, this was mainly influenced by SOC and, to a less extent, by the crystalline Al and Fe compounds.

From the correlations and regression models, it is obvious that the charge soil properties are mainly attributable to SOC and the additional influence of texture, which depends on the inherent mineralogy of the soil, as well as the ecological zone. Although the charge properties of tropical soils are supposed to be inherent to some extent, the charge properties tend to be dynamic due to their pH-dependent nature. The exchange properties are mainly attributable to soil pH, soil organic matter (SOM) [61] and mineral contents, such as Al and Fe oxides and hydroxides in the soil [44], along with their relationships with their respective pK_a and pH values in the soils. The contribution of soil pH depends on the dissociation constants of the soil mineral constituents, such as oxides and hydroxides of Al and Fe (pedogenic minerals) and SOM decomposition [44]. These soil mineral constituents form the foundation for each soil type and influence the inherent soil properties, which are rarely affected by soil management.

Despite the trends, it is estimated that agriculture in tropical and semi-arid agroecological zones without supplementary fertilizers is profitable for only six years compared to sixty-five years in temperate prairies. This highlights the significant influence of ecological zones [62], as these factors played a role in the observed patterns in agricultural expansion. This study presents two contrasting ecological conditions that have played a role in the observed trends in the properties of soils under agricultural expansion. In tropical conditions, SOM decomposition proceeds rapidly due to high temperatures. This hugely affects crop yields, particularly in the prevailing fertilizer-poor economy in SSA. Given the intense calls for agricultural intensification, chemical fertilizers alone cannot provide the premium soil quality required for sustained crop productivity. Thus, the inclusion of biochar [22] through co-applications and co-composting to stabilize SOM [63,64] in the soils is highly recommended. More importantly, conscious effort and knowledge about the Amazonian

Dark Earths could be applied, with a long-term aim of building Terra Preta Model soils. as proposed previously [65] and further described recently (Neina and Agyarko-Mintah, submitted). As the Terra Preta Model soil is built on the integrated utilization of decomposable wastes, it has the potential to protect planet health. The model soil could be integrated with chemical fertilizers to close the existing yield gaps.

5. Conclusions

Our results suggest that agricultural expansion, manifested by the duration of cultivation (farm types), had impacts on certain soil properties. This, however, differed in each of the two agroecological zones of Ghana. Cultivation affects SOC contents and soil fertility status and consequently, soil productivity. The Dompem soils had relatively higher SOC content, which decreased by margins of 17, 16 and 15% among the farm types, yielding a strong negative correlation with bulk density. Soil organic carbon was found to be a major driver of SEB and ECEC, which significantly decreased in accordance with the years of cultivation for these soils. This decline may be attributable to tillage, intense climatic conditions, such as high temperature, and favourable moisture contents, which causes rapid decomposition of SOM leading to a rapid decline. The decline was rapid in the first three years of cultivation. Furthermore, high rainfall patterns in the tropical ecozones may have caused the leaching of exchangeable bases, which decreased in relation to the years of cultivation, giving way to pedogenic Fe and Al minerals. With regards to the Adansam soils, only the δpH presented a decline in relation to the years of cultivation and the charge sign changed from negative to zero and positive, resulting in the largest decline within the first three years. This was also primarily influenced by SOC and, to a less degree, by the crystalline Al and Fe compounds. We, therefore, conclude that agriculture expansion without nutrient replenishment may lead to soil degradation, which is a major threat to food security and poverty alleviation. It is thus critical to intentionally and consciously adopt soil management practices that improve soil productivity and minimize the negative impacts on ecosystem services. These include co-applications of inorganic fertilizers, compost and manure with biochar or applications of biochar with compost to stabilize SOM. The long-term aim of building Terra Preta Model soils, as suggested previously, should also be encouraged. Policies that promote and enforce sustainable food production practices while enhancing the allocation of land for agriculture and conservation should be the topmost priority. Future research on suitable combinations of organic and inorganic fertilizers for specific soil types to ensure sustainable crop production should be conducted and recommendations transferred to farmers.

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Data Availability Statement: Data available on request due to privacy restrictions. The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the continuing nature of the study.

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