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Effects of soil management on aggregation and organic matter dynamics in sub-Saharan Africa

F. O. Ayuke[1]*, Z. Zida[2] and D. Lelei[3]

Fredrick Ouma Ayuke

*Lead author email: fredrick.ayuke@yahoo.com , fredrick.ayuke@uonbi.ac.ke

[1]Department of Land Resource Management and Agriculture Technology (LARMAT), Faculty of Agriculture and Veterinary Sciences, University of Nairobi, P.O Box 29053-00625, Nairobi, Kenya

[2]Alliance for Green Revolution in Africa (AGRA), PMB KIA 114, Accra, Ghana

[3]World Agroforestry Centre (ICRAF), P.O Box 30677-00100, Nairobi, Kenya

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Abstract

Maintenance of soil organic matter (SOM) is important for soil quality and agricultural productivity. However, little is known about the effects of management practices of different intensities on soil aggregation and SOM dynamics in tropical arable cropping systems of sub-Saharan Africa. We investigated the influence of land use practices and management intensity on soil aggregation and SOM dynamics across 12 long-term field experiments in eastern and western Africa. Aggregate size distribution and SOM were measured in arable systems under contrasting management intensities of high carbon, low carbon and a fallow. Aggregate stability indices and SOM were generally higher in the fallow compared to the arable systems. Fallowing and high carbon inputs in arable soils, significantly improved aggregate stability and carbon (C) and nitrogen (N) stabilization in whole soil, and in aggregate fractions. In contrast, no significant improvements in soil aggregation and C and N stabilization were found when organic inputs were either applied in low quantities or not applied at all, thus resulting in low carbon in soils. Our study showed that fallowing and long-term application of organic amendments alone or in combination with mineral fertilizers were the best among the practices tested in this study, for enhanced C and N stabilization in soils with the subsequent benefits of improving soil physical and chemical properties. These results emphasize the importance of management for sustaining soil quality. It is recommended that fallowing be an integral part of sustainable soil management strategies in these regions.

Key words: Soil aggregation, soil organic matter, carbon, nitrogen, management intensity

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Introduction

Soil aggregate stability, that is the ability of soil aggregates to remain intact when subjected to some stress and soil organic matter (SOM) dynamics have lately received much attention due to their role in sustainable ecosystem functioning and also because of concerns about global warming and climate change (Fonte *et al*., 2009; Gougoulias *et al*., 2014). Soil aggregates (i.e. a group of soil particles with a diameter size of less than 2 mm, that bind each other more strongly than adjacent particles), especially micro-aggregates (size diameter, 53 – 250 µm) formed within macro-aggregates (≥ 250 µm), protect SOM against microbial decay (Tisdall and Oades, 1982; Six *et al*., 2000; Bossyut *et al*., 2005) and can reduce surface crusting and soil erosion (Blanchart *et al*., 1999; Barthes and Roose, 2002; Spohn and Giani, 2011; Six and Paustian, 2014). Soil organic matter also binds mineral particles into aggregates (Tisdall and Oades, 1982) and stimulates the activities of soil biota (Six *et al*., 2004; Ayuke *et al*.,2011b). Soil C and N stabilization and consequently fertility, are mediated by the interactions between soil organic matter, soil structure and soil fauna abundance and diversity, all of which are affected by management practices (Six *et al*., 2004). Land use practices such as fallowing, tillage, organic and inorganic amendment application and crop rotation, have been shown to impact soil structure, which may lead to changes in SOM storage and turnover (Ayuke *et al*., 2011b; Paul *et al*., 2013). In several conceptual models, the increase of aggregate stability after addition of organic amendments to soil has been related to the decomposition dynamics of cauliflower green manure, wheat straw and cattle manure inputs (Abiven *et al*., 2009). The loss of SOM and subsequent deterioration of soil physical, chemical and biological soil quality due to continuous cropping, along with sub-optimal fertilizer use, frequently result in a decline in biomass productivity and crop yields, presenting great challenges to many farmers in sub-Saharan Africa (Sanchez *et al*., 1997). Despite the potential significant benefits of soil aggregation and increased SOM and related soil processes on soil quality, there is a general lack of knowledge about how these soil quality parameters are affected by management practices of varying intensities, and associated soil disturbance arising from agricultural activities. Due to the soil's capacity to sequester large amounts of organic C, an understanding of soil aggregation and SOM dynamics, and their influencing factors are important in addressing climate change and greenhouse gas mitigation efforts (Lal, 2011).

This study, therefore, investigated the effect of land use practices and management intensity (fallowing and organic inputs) on soil structure and SOM dynamics in long-term field trials across eastern (Kenya and Malawi) and western (Nigeria, Ghana, Burkina Faso and Niger) Africa. Specifically, the study sought to assess the effects of management practices on soil aggregation, and C and N stabilization in whole soil and aggregate fractions.

Materials and Methods

Study sites and sampling strategy

The study was conducted on 12 long-term field trials across the sub-humid to semi-arid tropical zones of eastern Africa (Embu, Kabete, Impala and Nyabeda in Kenya, and Chitala in Malawi) and western Africa (Tamale in Ghana, Ibadan in Nigeria, Sadore in Niger and Farakoba, Saria I, II and III in Burkina Faso) (Figure 1). A general characterization of the sites, including climate and soils, is presented in Table 1. The long-term trials were established between 1960 and 2003, and aimed at testing different management options for arable crop production such as organic versus mineral inputs, crop rotation, and tillage. All experiments in the selected sites were laid down in completely randomized block designs in three to four replications. For the present study, only three treatment blocks were selected and sampled. In our sampling scheme, only the arable treatments that according to previously available data had resulted in the highest C and lowest soil organic carbon C contents were included in the analysis (Table 2). At each site, a long-term fallow representing a relatively undisturbed reference was sampled. Depending on the site, the fallows consisted of grass fallow, forest or shrub land for at least 10 years before the time of sampling.

Soil sampling, pretreatment and analysis

One soil monolith measuring 25 cm long × 25 cm wide × 30 cm deep, was randomly sampled from each replicate plot (n = 3) between six to eight weeks after planting (July-September 2006 in the West African sites and February-July 2007 in the East African sites). The excavated soil was initially hand-sorted for macro-fauna separately at 0-15 and 15-30 cm soil depths as described in Ayuke *et al*. (2011a).

A representative subsample (about 500g) of the 0-15 and 15-30 cm soil depth layers of the monolith was gently passed through a 10 mm sieve by breaking up the soil along natural planes of weakness, air-dried and stored at room temperature. The soil was then separated into four water stable aggregate size fractions: (i) large macro-aggregates (size diameter > 2000 µm), (ii) small macro-aggregates (250 - 2000 µm), (iii) micro-aggregates (53 – 250 µm), and (iv)silt + clay sized particles (< 53 µm), using the method described by Elliott (1986). Briefly, 80g of air-dried soil was transferred to a 2 mm sieve, placed in a receptacle filled with deionized water, and left to slake for 5 min, after which the 2 mm sieve was manually moved up and down 50 times in 2 minutes. The procedure was repeated using the material that passed through the 2 mm sieve, using a 250 µm sieve and subsequently a 53 µm sieve. A representative 250 ml subsample was taken from the suspension containing the <53 µm silt and clay sized particles to determine the weight of the smallest fraction. Soil aggregates retained on each sieve were backwashed into pre-weighed containers, oven-dried at 105°C over-night and weighed.

After wet sieving, oven drying and weighing, the large and small macro-aggregates retained were combined according to their relative weight or proportions to obtain total macro-aggregates. The total macro-aggregates were then used for the separation of micro-aggregates within macro-aggregates as follows: Micro-aggregates (53-250 µm) occluded within macro-aggregates were isolated using a device described by Six *et al.* (2000), which completely breaks up macro-aggregates with minimal disruption of micro-aggregates. About 5 g of the macro-aggregates were transferred to the device holding a 250 µm mesh screen and shaken with 50 glass beads (diameter 4 mm) to break the macro-aggregates. The micro-aggregates released were immediately flushed through the 250 µm sieve and deposited onto a 53-µm sieve by a continuous flow of water through the device. The material on the 53 µm sieve was then wet-sieved as described above, 50 times in 2 minutes, to isolate the stable micro-aggregates from the

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silt and clay. The micro-aggregate fractions (53-250 µm) were oven-dried (60°C) for 48 hours and weighed. Sand and coarse particulate organic matter retained on the 250 µm mesh screen were washed off, oven-dried, and weighed. The silt and clay, and silt and clay within macro-aggregates were calculated from the total volume of the suspension and the volume of the subsample. Mean weight diameter was determined as the sum of the weighted mean diameters of all fraction classes.

For measurement of total soil organic C and N content, 1-2 g of the whole soil (before fractionation) and aggregate fraction soil samples were taken and ground. About 30 mg of the samples were weighed out in aluminium capsules and sent to the University of California at Davis, USA for analyses of total carbon and nitrogen. These were determined using the Dumas combustion method with a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 Integra C-N isotope ratio mass spectrometer (Sercon LTD, Cheshire, United Kingdom).

Statistical analysis

The data obtained on soil aggregate fractions, and soil C and N were subjected to analysis of variance with R Studio Version 0.97.449 (R Core Team, 2013). The Linear Mixed Model was fitted by Restricted Maximum Likelihood (RELM) procedure using the ImerTest package (Kuznetsova *et al*., 2014). This procedure allows for inclusion of both fixed- and random-effects terms in the model such that profiled deviance of RELM criterion is optimized for the parameter estimates (Bates *et al*., 2015). Site and treatment, and their interactions were included in the model as fixed factors, whereas block was defined as a random factor. However, only overall treatment effects are presented in the results. Aggregate fractions, whole soil and aggregate-associated Soil C and N were analyzed independently for two soil depths (0-15 cm and 15-30 cm). The statistical significance was determined at $p \leq 0.05$ and where statistical differences were detected, Tukey´s post hoc multiple comparisons tests were performed.

Results

Water stable aggregate indices

Management practices and intensity had significant influences on water stable aggregates at both 0-15 and 15-30 cm depths. The differences in aggregate size distribution were reflected in mean weight diameter, which were consistently lower in the arable (high carbon and low carbon) treatments compared to fallow treatment (Table 3). At 0-15 cm soil depth, the proportion of large macro-aggregates was significantly higher in fallow than in the arable (high carbon and low carbon) treatments, but the difference between high carbon and low carbon treatments was not statistically significant (Table 3). Differences in the proportions of micro-aggregates within macro-aggregates and silt and clay within macro-aggregates showed the same pattern as differences in large macro-aggregates. The proportion of small macro-aggregates was significantly higher in the fallow (45.72 g 100 g^{-1} total soil) than in high carbon treatment (42.48 g 100 g^{-1} total soil), which, in turn, small macro-aggregates was significantly higher than in the low carbon (38.32 g 100 g^{-1} total soil) treatment. However, a reverse trend was observed for the proportions of micro-aggregates, silt and clay and coarse particulate organic matter, and these followed the order low carbon > high carbon > fallow treatments (Table 3). At 15-30 cm soil depth, the proportion of

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the aggregate fractions was highly variable across treatments. The proportion of small macro-aggregates was significantly higher in the fallow than in the arable (high carbon and low carbon) treatments, whereas the proportion of micro-aggregates was significantly higher in the arable (high carbon and low carbon) treatments than in the fallow treatment (Table 3). Differences in the proportion of silt and clay showed the same pattern as observed for micro-aggregates at the 0-15 cm depth, as it followed the order low carbon > high carbon > fallow treatments. Management practices, however, had no significant effects in the proportions of large macro-aggregates, coarse particulate organic matter, micro-aggregates within macro-aggregates, silt and clay within macro-aggregates and the mean weight diameter at 15-30 cm soil depth.

Whole soil and aggregate-associated carbon

Management practices and intensity affected the concentration of carbon in whole soil, as well as in the aggregate fractions. The concentration of C for the micro-aggregates within macro-aggregates fraction, followed the order high carbon > fallow treatments > low carbon, whereas for coarse particulate organic matter and silt and clay within macro-aggregates the concentration of C did not differ between treatments. However, the levels of C in whole soil, and in all the other aggregate fractions, were significantly higher in the fallow than in high carbon treatments, which in turn, were significantly higher than in the low carbon treatments at 0-15 cm soil depth (Table 4). At 15-30 cm, the concentration of C in small macro-aggregates fraction was significantly higher in the fallow treatment than in the arable (High carbon and low carbon) treatments, whereas, the concentration of C in the micro-aggregates within macro-aggregates fraction was significantly lower in low carbon (12.95 g C 100 g^{-1} total soil) treatments than in fallow (15.17 g C 100 g^{-1} total soil) and high carbon (14.72 g C 100 g^{-1} total soil) treatments. The concentration of C in micro-aggregates was significantly higher in fallow than in low carbon treatment, although the concentration in high carbon did not differ from either fallow or low carbon treatments. However, the concentration of C in whole soil and in all the other aggregate fractions (large macro-aggregates, silt and clay, coarse particulate organic matter and silt and clay within macro-aggregates) did not differ between the treatments and hence were not affected by management practices (Table 4).

Whole soil and aggregate-associated nitrogen

Nitrogen concentrations in whole soil and aggregates showed similar trends to C at 0-15 cm depth. Although no treatment differences were observed for both coarse particulate organic matter and silt and clay within macro-aggregates, the concentration of N in micro-aggregates within macro-aggregates fraction followed the order high carbon > fallow > low carbon treatments. However, the concentrations of N for all the other fractions were significantly higher in fallow > high carbon > low carbon treatments (Table 5). At 15-30 cm, no significant differences in concentrations of N were observed for coarse particulate organic matter and silt and clay within macro-aggregates, although the level of N in micro-aggregates within macro-aggregates fraction was significantly higher in fallow > high carbon > low carbon treatments. Fallow, on the other hand had higher N in the small macro-aggregates fraction than in the arable treatments, but the concentrations of N in micro-aggregates and silt and clay were significantly lower in low carbon treatments than in either fallow or high carbon treatments. The concentrations of N in whole soil and large macro-aggregates fraction were significantly higher in fallow than in low carbon treatment, but high carbon did not differ from them (Table 5).

Discussion

At most sites, management comparisons of fallow, high C and low C arable systems were not uniform, and not all of the treatments involved addition of organic residues. In view of the large variability in the data, results can be considered robust whenever differences in aggregation and SOM between treatments were significant.

Aggregate stability

Fallowing, and long-term application of organic inputs resulted in a buildup of soil organic matter, and this significantly enhanced aggregate stability and C and N pools especially at top (0-15 cm) and at subsoil (15-30 cm) depths for some soil fractions (Table 4). Our study has shown that long-term application of organic inputs such as crop residues, leaf litter and cattle manure resulted in higher stable aggregation, but not to the extent of the fallow, which is attributed to absence of soil disturbance and higher accumulations of organic matter in the fallow compared to arable systems. Our results corroborate findings by Ayuke *et al.* (2011b) who showed higher aggregate stability under fallow compared to the arable system. Higher proportions of aggregate fractions < 250 µm in arable systems compared to fallow could be due to the effect of tillage practices which result in breakup of the macro-aggregates into smaller fraction aggregates such as micro-aggregates as well as silt and clay. Soil tillage indirectly affects soil aggregate stability, mainly through its influence on soil fauna, soil moisture, and on the redistribution of SOM (Tisdall and Oades, 1982; Paul *et al.*, 2013). Tillage also breaks down aggregates and exposes organic matter to microbial attack, thus stimulating C and N oxidation and the loss of labile organic matter which binds micro-aggregates into macro-aggregates (Kushwaha *et al.*, 2001).

The relatively higher proportion of small macro-aggregates in arable systems under high C inputs than under low C inputs can be attributed to regular addition of organic matter through crop residues, leaf litter and pruning, manure and additional root biomass added to soil due to fertilizer-enhanced plant growth. This results in greater C availability and enhanced microbial and macro-faunal activity which lead to the formation of aggregates (Six *et al.*, 2004; Kibunja *et al.*, 2010;. Ayuke *et al.*, 2011b). Probably, when organic resources are incorporated into the soil, organic matter gradually decomposes to produce humic substances and bacterial biomass, which in turn releases polysaccharides which serve as binding agents, and fungal mycelia binding soil particles into aggregates (Bossuyt *et al.*, 2005; Aoyama *et al.*, 1999). Lack of organically generated binding agents, possibly explain why significantly higher proportions of aggregate fractions < 250 µm (e.g. micro-aggregates, silt and clay, and coarse particulate organic matter), were found under low C input systems compared to high C input systems. Singh *et al.* (2007) have similarly shown that addition of animal manure with mineral fertilizers in rice–wheat–cowpea rotation systems, improved the aggregation of soil particles.

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Whole soil and aggregate-associated carbon and nitrogen

Highest C and N were recorded in the fallow sites, and the high carbon input arable systems had higher C and N than low carbon input arable systems. High carbon inputs through organic amendment applications increased the C and N content of whole soil and in most of the fractions, especially at the 0-15cm depth. Higher C and N in the fallow land could be attributed to the accumulation of organic matter which upon decomposition, mineralize and release nutrients that are then added to the soil. Incorporation of organic resources facilitates decomposition processes of organic matter such that the free primary particles are cemented together into micro-aggregates by persistent binding agents such as roots, fungal hyphae and polysaccharides). As such, humification of organic matter stimulates the accumulation of C and N in aggregates. The micro-aggregates further bind to form SOM rich macro-aggregates, so the SOM can then be physically protected within the macro-aggregates. This explains why the highest micro-aggregates within macro-aggregates fraction C and N was recorded under high carbon input systems compared to fallow and low carbon input system, and these results indicate that macro-aggregates are important in C and N stabilization in soil as also observed by Sodhi *et al*. (2009) and Ayuke *et al*. (2011b). Among the soil management practices studied, C and N concentrations were generally higher in the silt and clay fractions, especially silt and clay within macro-aggregates, compared to all other fractions. Soils high in clay, and iron and aluminum oxides, such as the Nitisols of some of our study sites (for example, Embu and Kabete in Kenya), have been shown to respond positively to organic inputs in that they have a high C and N stabilization in aggregate fractions (Gentile *et al*., 2010; Ayuke *et al*., 2011b). Results on total C and N in whole soil in fallow and high carbon input practices compared to low carbon input practice is an indicator of C and N build-up as a result of the persistent addition of organic resources and cumulative soil organic matter. Rapid decomposition of organic resources and resultant conversion of the organic C into recalcitrant or resistant forms (Dick and Gregorich, 2004), and cumulative addition of N through mineral fertilizers (Sodhi *et al*., 2009) promotes sequestration of C and N, respectively, into the soil.

Our results showed that fallowing and long-term application of organic resources alone or in combination with mineral fertilizers observed at study sites, enhanced C and N stabilization with the benefits of improving soil physical and chemical properties. Due to the capacity of soils to sequester large amounts of organic carbon, an understanding of soil aggregation and soil organic matter dynamics, and their influencing factors are important in addressing climate change and greenhouse gas mitigation efforts. Arable land in sub-Saharan Africa faces numerous challenges and among them, an increasing population, dwindling household land acreage, and reduced or abandoned fallow practices. These results show the importance of soil conservation practices for sustaining soil quality, and the importance of fallowing as an integral part of sustainable management strategies in these regions.

Conclusion

Fallowing and high carbon inputs in arable soils significantly improved aggregate stability and C and N stabilization in the top (0-15 cm) of arable soils. In contrast, no significant improvements in soil aggregation and C and N stabilization were found when organic inputs were applied in low quantities as observed in the low carbon input soils. This study has shown that fallowing and long-term application of organic amendments are the best among the soil improving management practices tested in this study, for enhanced C and N stabilization with the benefits of improving soil physical and chemical properties.

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Table 1: Location and characteristics of the study sites

Environmental Parameters	Sites **Embu, Kenya**	**Kabete, Kenya**	**Impala, Kenya**	**Nyabeda, Kenya**	**Chitala, Malawi**	**Ibadan, Nigeria**	**Tamale, Ghana**	**Sadore, Niger**	**Farakoba, Burkina Faso**	**Saria I, II, III, Burkina Faso**
Altitude asl. (m)	1480	1700	1337	1420	606	200	185	250	405	300
Latitude and Longitude	0° 30′ S; 37° 30′ E	1° 15' S; 36° 41' E	0° 08' N; 34° 25' E	0° 06' N; 34° 36' E	13° 40' S; 34° 15' E	7° 30' N; 3° 54' E	9° 25' N; 1° 00' W	13° 15' N; 2° 17' E	11° 06' N; 4° 20' W	12° 16' N; 2° 09' E
Mean Annual temp (°C)	20	18	23	23	22	27	29	33	28	33
Mean annual rainfall (mm)	1450 Bimodal	1000 Bimodal	1800 Bimodal	1800 Bimodal	800 Unimodal	1200 Bimodal	1200 Unimodal	550 Unimodal	850 Unimodal	800 Unimodal
Climate (FAO)	Sub-humid	Sub-humid	Humid	Humid	Sub-humid	Humid	Semi-arid	Semi-arid	Sudano-Sahelian	North-Sudanian
Soil type (WRB, 2015)	HUMIC NITISOL	HUMIC NITISOL	HUMIC FERRALSOL	HUMIC FERRALSOL	TYPIC FERRALSOL	DYSTRIC REGOSOL	FERRIC LUVISOL	FERRALIC ARENOSOL	FERRIC LUVISOL	FERRIC LIXISOL
Texture sand, silt, clay (%)	Clay 3, 22, 75	Clay 11, 22, 67	Clay 13, 17, 70	Clay 9, 21, 70	Sandy clay 60, 5, 35	Sandy 87, 6, 7	Sandy 90, 4, 6	Sandy 92, 3, 5	Loamy sand 74, 19, 7	Sandy loam 53, 36, 11

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Table 2: Description of selected sites. # refers to management treatments: 1 = crop rotation, 2 = tillage, 3 = organic inputs, 4 = inorganic fertilizer HC = high carbon; LC = low carbon

Trial site	Year established	Treatments		
		Fallow	**Arable- HC**	**Arable-LC**
Embu	1993	Fallow-woodland/shrubland since 1993	#1=Cont. maize, 2=Hand hoeing, 3=*Leucaena leucocephala* (5 Mg ha^{-1}), 4=no fertilizer	#1=Cont. maize, 2=Hand hoeing, 3=no organic inputs, 4=no fertilizer
Kabete	1976	Fallow-Bushland since trial establishment in 1976	#1=Maize-bean rotation, 2=Hand hoeing, 3=10 Mg ha^{-1} manure, 4=CAN (120 kg N ha^{-1}) and TSP (52.8 kg P ha^{-1}) fertilizers	#1. Maize-bean rotation, 2=Hand hoeing, 3= no organic inputs, 4=no fertilizer
Impala	2000	Fallow-shrubland nearby since trial establishment in 2000	#1=Maize-*Tephrosia candida* relay/rotation, 2=Hand hoeing, 3=*T. candida* residues (5 Mg ha^{-1}), 4= Blanket P , no N fertilizer	#1= Cont. maize, 2=no till, 3=no organic inputs, 4=no fertilizer
Nyabeda	2003	Fallow-shrubland nearby since trial establishment in 2003	#1. Maize-soybean rotatn, 2=no till, 3=Maize stover residues (2 Mg ha^{-1}), 4=NPK fertilizer (60:60:60)	#1=Maize-soybean rotation, 2=hand hoeing, 3=no organic inputs, 4=NPK fertilizer (60:60:60)
Chitala	1995	Grass fallow since trial establishment in 1995	#1=Maize-pigeon pea rotation, 2=Tractor till, 3=Crop residues: stem + leaves, 4=$(NH_4)_2SO_4$ fertilizer (96 kg N ha^{-1} yr^{-1})	#1=Cont. maize, 2=Tractor till, 3=no organic inputs, 4=no fertilizer
Ibadan	1996	Bushland fallow since 1986 adjacent to the experimental plots	#1=Maize-cowpea rotation, 2=Minimum tillage-light surface hoeing, 3=*S. siamea* (5 Mg ha^{-1}), 4=fertilizer-NPK (60:30:30 kg ha^{-1} yr^{-1})	#1=Maize-cowpea rotation, 2=Minimum tillage-light surface hoeing, 3=no organic inputs, 4=no fertilizer

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Table 2 (Continued) Description of selected sites. # refers to management treatments: 1 = crop rotation, 2 = tillage, 3 = organic inputs, 4 = inorganic fertilizer

Tamale	1996	Grass fallow strip since 1996	#1=Cont. maize, 2=Zero till-hand pulling/slashing of weeds, 3=no organic inputs, 4=no fertilizer	#1=Cont. maize, 2=Bullock plough-hand hoeing of weeds, 3=no organic inputs, 4=no fertilizer
Sadore	1986	Fallow-shrubland within the experimental site since 1986	#1=Millet-cowpea rotation, 2= Animal traction + ridging , 3=residues applied, 4=fertilizer (30kg N, 13 kg P ha^{-1})	#1=Cont. millet, 2= Hand hoeing, no ridging, 3=residues applied, 4=fertilizer (13 kg P ha^{-1})
Farakoba	1993	Grass fallow within the experimental site since trial; establishment in 1993	#1. Cont. sorghum, 2=Tractor till, 3=compost (5 Mg ha^{-1}), 4=PK fertilizer (25:14)	#1. Cont. sorghum, 2=tractor till, 3=no organic inputs
Saria I	1960	Grass- fallow since trial establishment in 1959 (Common for all the Sarias)	#1=Sorghum-cowpea rotation, 2=Tractor till, 3=manure (5 Mg ha^{-1} every 2 yrs), 4=NPK fertilizer (100 kg ha^{-1}) and Urea (50 kg ha^{-1}) every 2 years	#1=Cont. sorghum, 2=Tractor till, 3=manure (5 Mg ha^{-1} every 2 yrs), 4=NPK fertilizer (100 kg ha^{-1}) and Urea (50 kg ha^{-1}) every 2 years
Saria II	1980	See Saria I	#1=Cont. sorghum, 2=Tractor till, 3=10 Mg ha^{-1} manure, 4=fertilizer- 23kg N ha^{-1}	#1=Cont. sorghum, 2=Tractor till, 3=no organic inputs, 4=no fertilizer
Saria III	1990	See Saria I	#1. Cont. sorghum, 2=Oxen plough, 3=Manure (10 Mg ha^{-1}), 4=NPK fertilizer (100 kg ha^{-1} yr^{-1}) and Urea (50 kg ha^{-1} yr^{-1})	#1=Cont. sorghum, 2=Hand hoeing (5cm depth), 3=Manure (10 Mg ha^{-1}), 4=NPK fertilizer (100 kg ha^{-1} yr^{-1}) and Urea (50 kg ha^{-1} yr^{-1})

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Table 3: Aggregate fraction distribution in the surface (0-15 cm) and sub-surface (15-30 cm) soil layers

	------------------------Aggregate fraction (g 100 g-1 total soil)------------------				---------------Aggregate fraction (g 100 g-1 TM)--------			
Treatment	LM (>2000µm)	SM (250-2000µm)	Mi (53-250µm)	sc (≤53)	cPOM (≥250µm)	mM (53-250µm)	scM (≤53)	**MWD (mm)**
Depth (0-15 cm)								
Fallow	19.03 (3.3)A	45.72 (3.5)A	30.74 (3.3)C	4.52 (0.4)C	36.98 (6.8)C	45.28 (4.6)A	17.73 (2.8)A	1.51 (0.1)A
High-C	8.15 (1.7)B	42.48 (4.0)B	41.70 (3.5)B	7.67 (0.5)B	44.00 (7.4)B	42.30 (5.3)B	13.70 (1.4)B	0.95 (0.1)B
Low-C	6.62 (1.5)B	38.32 (3.7)C	46.11 (3.0)A	8.95 (0.6)A	46.79 (7.5)A	41.00 (5.7)B	12.21 (2.2)B	0.83 (0.1)B
***p*-value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.004**	**<0.001**	**<0.001**
Depth (15-30 cm)								
Fallow	15.83 (2.5)A	49.46 (3.9)A	30.09 (3.3)B	4.62 (0.4)C	36.30 (6.8)A	46.26 (4.8)A	17.45 (2.8)A	1.40 (0.1)A
High-C	13.80 (2.7)A	45.67 (3.8)B	34.79 (3.3)A	5.75 (0.5)B	39.93 (7.1)A	44.49 (5.5)A	12.57 (1.1)A	1.26 (0.1)A
Low-C	13.14 (2.4)A	43.02 (3.9)B	37.32 (3.4)A	6.52 8.05)A	38.59 (7.0)A	45.68 (5.1)A	15.58 (2.3)A	1.20 (0.1)A
***p*-value**	**0.280**	**<0.001**	**<0.001**	**<0.001**	**0.370**	**0.729**	**0.124**	**0.062**

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Table 4: Whole soil C (g kg-1 soil) and aggregate fraction C (g 100 g-1 total soil)

Treatment	WS (g kg-1 soil)	LM (>2000µm)	SM (250-2000µm)	Mi (53-250µm)	sc (≤53)	cPOM (≥250µm)	mM (53-250µm)	scM (≤53)
		(g 100 g-1 total soil)						
Depth (0-15 cm)								
Fallow	18.34 (2.6)A	19.33 (3.3)A	16.55 (2.7)A	19.21 (2.7)A	26.70 (2.7)A	12.88 (2.6)A	15.71 (1.9)B	24.38 (2.1)A
High-C	15.53 (2.1)B	15.61 (2.5)B	14.38 (2.2)B	15.82 (2.0)B	22.14 (2.0)B	11.08 (2.3)A	17.53 (2.5)A	25.39 (2.6)A
Low-C	12.94 (1.8)C	11.49 (2.0)C	11.76 (1.9)C	13.58 (1.7)C	19.41 (1.6)C	15.17 (3.3)A	13.77 (1.9)C	24.24 (1.8)A
***p*-value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.366**	**<0.001**	**0.605**
Depth (15-30 cm)								
Fallow	12.75 (1.9)A	13.66 (2.3)A	13.94 (1.9)A	13.60 (1.9)A	20.24 (2.0)A	11.16 (1.9)A	15.17 (1.8)A	23.52 (1.8)A
High-C	12.61 (1.8)A	13.16 (2.2)A	12.40 (1.8)B	13.23 (1.8)AB	19.77 (1.9)A	11.81 (2.4)A	14.72 (2.2)A	22.17 (1.9)A
Low-C	11.95 (1.7)A	12.13 (1.9)A	12.22 (1.7)B	12.26 (1.7)B	18.34 (1.8)A	9.84 (1.7)A	12.95 (1.7)B	21.15 (1.6)A
***p*-value**	**0.170**	**0.146**	**0.004**	**0.041**	**0.121**	**0.105**	**0.008**	**0.170**

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Table 5: Whole soil N (g kg-1 soil) and aggregate fraction N (g 100 g-1 total soil)

Treatment	WS (g kg-1 soil)	LM (>2000µm)	SM (250-2000µm)	Mi (53-250µm)	sc (≤53)	cPOM (≥250µm)	mM (53-250µm)	scM (≤53)
		(g 100 g-1 total soil)						
Depth (0-15 cm)								
Fallow	1.59 (0.2)A	1.58 (0.3)A	1.44 (0.2)A	1.62 (0.2)A	2.36 (0.3)A	0.81 (0.2)A	1.25 (0.2)B	2.24 (0.2)A
High-C	1.35 (0.2)B	1.25 (0.2)B	1.18 (0.2)B	1.29 (0.2)B	1.92 (0.2)B	0.75 (0.2)A	1.39 (0.2)A	2.28 (0.2)A
Low-C	1.10 (0.2)C	0.96 (0.2)C	0.96 (0.2)C	1.10 (0.1)C	1.63 (0.1)C	1.01 (0.2)A	1.08 (0.1)C	2.34 (0.2)A
***p*-value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.378**	**<0.001**	**0.728**
Depth (15-30 cm)								
Fallow	1.13 (0.2)A	1.14 (0.2)A	1.17 (0.2)A	1.15 (0.2)A	1.77 (0.2)A	0.75 (0.1)A	1.20 80.1)A	2.20 (0.2)A
High-C	1.09 (0.2)AB	1.01 (0.2)AB	1.02 (0.2)B	1.09 (0.2)A	1.70 (0.2)A	0.72 (0.2)A	1.17 (0.2)B	2.05 (0.2)A
Low-C	1.03 (0.2)B	0.94 (0.2)B	0.99 (0.1)B	1.02 (0.1)B	1.54 (0.1)B	0.64 (0.1)A	1.03 (0.1)C	2.01 (0.1)A
***p*-value**	**0.026**	**0.002**	**<0.001**	**0.003**	**0.008**	**0.184**	**0.007**	**0.164**