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Farming system-induced variability of some soil properties in a sub-humid zone of Ghana

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Abstract

This study assessed the effects of different farming systems, namely woodlot (WL), alley farming (AL), conventional tillage (CT) and natural fallow (NF) on the variability of organic carbon (OC) content and mean weight diameter (MWD) of a degraded Ferric Acrisol in the sub-humid zone of Ghana. The soils under woodlot accumulated the highest amount of organic carbon (18.6 g kg^{-1}) with the least spatial variability apparently due to the greater additions of litter and minimum tillage. The conventionally tilled soil had the least OC content (13.1 g kg^{-1}). Similar to the OC content, the woodlot soils also had the highest aggregate stability (MWD = 1.78 mm) and the least spatial variability. The stability of soil aggregates under the farming systems was greatly influenced by OC content; there was a good correlation between OC and MWD ($r > 0.62^{**}$). Correlograms showed that OC and MWD are space dependent. The correlation length for OC under the different farming systems followed the order WL > NF > AL > CT, indicating that WL ensured a greater uniform distribution soil organic matter. The spatial distribution in MWD followed the same trend observed for OC. The MWD in the other farming systems was poorly related from point to point with shorter k-values, suggesting lack of uniformity due to low accumulation of OC. Generally, the woodlot system appeared to be a better, low-input restorer of soil productivity.

Introduction

The search for new cropping systems for the tropics has intensified in recent years because many traditional cropping systems such as shifting cultivation have been destabilised due to rapid population growth (UNEP, 1988). Increased pressure on land has led to the decrease in fallow periods so that once cleared, the same land is cultivated continuously with no period of regeneration. This results in mining of soil nutrient and reduction in productivity. Efforts to increase food production in the tropics using high-input modern technologies have not produced desirable results due to prohibitive investment costs and/or land degradation which has been accelerated through the use of these technologies.

Agroforestry systems have been proposed as a means of arresting the rapid deterioration of soils due to high population pressure and sustaining soil productivity (Kang et al., 1981). These systems combine the cultivation of agricultural crops and tree plants, preferably leguminous species, of varying longevity arranged either temporally (woodlot) or spatially (alley cropping) with leguminous tree species as hedgerows (3 m × by 0.5 m spacing). Over the past two decades, agroforestry has been widely promoted in Ghana, but critical evaluations of the system remain still scanty (Dowuona et al., 1998; Tete-Mensah et. al., 1998).

An important aspect of agroforestry, which has hitherto not been well studied relates to its use in the management of soil variability. Variability of soil properties, especially those which change rapidly in the short term in the field is undesirable because this may lead to different maturity rates of crop and

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poor crop quality. Thus, the assessment of variability of soil properties is important because the effective management of soils depends on a good knowledge and quantification of the degree of variability of its properties (Onofiok, 1993).

The aim of this study is to assess the effects of woodlot, alley farming, conventional tillage and fallow systems on the variability of organic matter and aggregate stability of soils, which occur within an agroforestry project located in a degraded sub-humid zone of Ghana.

Materials and methods

Site characteristics, soils, farming systems and sampling

The study site is located at latitude 5° 47′ N and longitude 0° 21′ W in Ghana, West Africa. The site, which was once a forest (Lane, 1962) currently receives a mean total annual rainfall of 1040 mm and has a mean annual daily temperature of 24.2 °C (MSD, 1990). Deforestation for farming and increased lumbering at the site have resulted in the degradation of the original forest vegetation, which is now a derived-savanna ecosystem.

The soils at the study site are classified as Ferric Acrisols (WRB, 1998) and are among the most important agricultural soils in Ghana and elsewhere in the sub-humid tropics. They are derived from weathered granite in an upland site on the landscape. They are dark brown at the surface and become red in the sub-soil. The topsoil is slightly acidic while the cation exchange capacity is below 16 cmol (+) kg^{-1}. The texture varies from sandy loam to sandy clay loam at increasing depth. The structure is fine, medium crumbly, changing to medium sub-angular blocky in the subsoil, which also contains many quartz and ironstone gravels. Kaolinite is the dominant clay mineral with minor amounts of haematite and goethite (Dowuona et al., 1998).

Different farming systems were established at the site within an agroforestry appraisal project. The systems comprise (i) an 8-year old *Leucaena leucocephala* woodlot (WL), (ii) an 8-year old alley farm with either cassava (AC) or maize (AM) seasonally cultivated between hedgerows of *Leucaena leucocephala*, (iii) an adjacent land that has been under natural fallow (NF) for about 8 years and (iv) a plot of land that has been continuously tilled (slash and burn) for about the same period using conventional simple implements (CT). These farming systems occur on the same soil at the same topographical site, namely, at the upland section of the landscape.

Undisturbed large clods (15 – 25 mm) and disturbed soil samples were taken along unidirectional transects of 85 m long at 5 m interval at a depth of 0 –0.15 m from each of the farming systems. Samples from the 1st point (0 m) and last point (85 m) were discarded to eliminate edge effect. In order to establish reliability of data and also extrapolation of data, two modal profiles, one under the woodlot and the other under the natural fallow were dug and both disturbed and undisturbed samples collected from each genetic horizon. The disturbed soil samples were used for the determination of organic carbon while the undisturbed clods (15 – 25 mm) were used for the determination of mean weight diameter (MWD).

Laboratory and data analysis

The organic carbon content of the soils was determined by the wet combustion method of Walkley and Black (1934). In determining the MWD, samples of the undisturbed clods were placed on a nest of seven sieves ranging from 9 mm down to 0.20 mm. The set-up was then placed on a shaker and subjected to shaking at a frequency of 80 Hz for 3 min. The weight of the soil aggregate on each sieve after the shaking was determined and used to calculate the MWD as an index of aggregate stability according to Hillel (1980):

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i W_i \tag{1}$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving and W_i is the percentage weight of aggregates in that size range.

There were 16 data points for each soil property and each farming practice. The data obtained were first subjected to descriptive statistical analysis and variability is expressed in terms of means, variances and coefficient of variation. Additionally, we also assessed the spatial variability of soil properties under each farming system using the auto-correlation function, r_k, given by:

$$r_k = \frac{c_k}{c_0} = \frac{c_k}{\sigma^2} \tag{2}$$

Table 1. Organic carbon content and mean weight diameter of the soils under the different farming systems

Distance (m)	Organic carbon (g kg^{-1})[a]					Mean weight diameter (mm)[a]				
	WL	AC	AM	NF	CT	WL	AC	AM	NF	CT
5	18.4	15.2	11.0	16.1	13.7	1.79	1.56	1.34	1.52	1.43
10	19.6	13.0	11.1	15.5	12.4	1.84	1.42	1.36	1.24	1.24
15	20.0	13.4	14.4	12.5	11.6	1.86	1.46	1.52	1.17	1.14
20	19.6	12.3	12.5	13.9	13.1	1.86	1.37	1.44	1.26	1.41
25	19.0	13.7	16.0	12.3	14.3	1.70	1.49	1.57	1.14	1.47
30	22.0	12.9	12.9	13.4	12.7	1.86	1.36	1.51	1.37	1.28
35	19.6	14.3	13.1	14.1	13.7	1.79	1.57	1.39	1.29	1.37
40	19.0	14.7	15.7	13.1	13.3	1.82	1.50	1.44	1.22	1.36
45	18.7	15.6	12.4	16.6	14.4	1.78	1.52	1.47	1.34	1.28
50	17.9	13.2	13.4	15.8	14.1	1.74	1.49	1.40	1.50	1.42
55	18.4	16.5	15.3	15.1	13.6	1.77	1.56	1.53	1.36	1.39
60	17.6	14.5	14.0	14.3	11.8	1.75	1.35	1.44	1.28	1.11
65	17.1	12.5	14.3	14.8	15.1	1.83	1.37	1.51	1.51	1.28
70	16.3	15.8	13.1	13.3	12.3	1.68	1.58	1.44	1.21	1.21
75	17.4	13.4	14.4	15.8	13.4	1.76	1.49	1.49	1.39	1.32
80	17.2	12.2	13.0	15.6	11.9	1.71	1.52	1.46	1.44	1.19
Mean	18.6	14.0	13.5	14.5	13.1	1.78	1.48	1.46	1.33	1.31
SE[b]	±0.4	±0.3	±0.4	±0.3	±0.3	±0.01	±0.02	±0.02	±0.03	±0.03
CV(%)[c]	7.5	9.5	10.8	9.2	7.7	3.3	5.4	4.4	9.1	8.3

[a] WL = woodlot; AC = alley cassava; AM = alley maize; NF = natural fallow; CT = conventional tillage.
[b] SE = standard error.
[c] CV = coefficient of variation.

with:

$$c_k = \frac{1}{n-k-1}\sum_{i=1}^{n-k}(x_i - <x>)(x_{i+k} - <x>) \tag{3}$$

where, C_k is the auto correlation for separation (or lag) k, C_0 is the value of C at lag 0 and is equal to the total variance (σ^2), x_i is the observation at the ith position, $x_{(i+k)}$ is the observation at the $(i + k)$th position, k is the distance between adjacent sampling points (or lag), n is the total number of observations and <x> is the sample mean. For the determination of r_k values, we used algorithms published by Campbell (1984). A graph of r_k against k gives the correlogram and depicts the correlation of properties over space. Whether a soil property is correlated or not over space within any farming system is usually assessed by determining the distance over which a significant correlation exists. This distance is commonly referred to as the integral scale or correlation length in Geo-statistics. In this study, the correlation length is taken as the k-value at which r_k reduces to $1/e$ (with e being the base of the natural logarithm). The value, $1/e$, though somewhat arbitrary, has been used by many authors to determine the correlation length of soil properties (Kutilek and Nielson, 1994).

Table 2. Profile distribution of organic carbon content and mean weight diameter

Horizon	Depth	Profile 1 (woodlot)		Profile 2 (natural fallow)	
		OC[a]	MWD[a]	OC[a]	MWD[a]
	(m)	(g kg^{-1})	(mm)	(g kg^{-1})	(mm)
Ap	0.00–0.13	19.0	1.79	15.1	1.35
Au1	0.13–0.26	10.0	1.41	9.6	0.82
Bt	0.26–0.43	6.8	0.90	5.6	0.61
Btc	0.43–0.61	5.3	0.81	4.9	0.52
B2tc	0.61–0.80	4.6	0.89	4.2	0.59
B3tc	0.80–1.10	4.1	1.00	3.8	0.62
C	1.10–1.50+	2.7	1.10	2.5	0.90

[a] OC = organic carbon; MWD = mean weight diameter.

Results and discussion

General variability of soil properties

Organic carbon (OC) content (Table 1) was generally higher for the soils under the WL (18.6 ± 0.4 g kg^{-1}) than those under the AC (14.0 ± 0.3 g kg^{-1}), AM (13.5 ± 0.4 g kg^{-1}), NF (14.5 ± 0.3 g kg^{-1}) and CT (13.1 ± 0.3 g kg^{-1}). The OC content ranged from 16.3 g $kg^{-1}$to 22 g kg^{-1}, 12.2 to 16.5 g kg^{-1}, 11.0 to 16.0 g kg^{-1}, 12.3 – 16.6 g kg^{-1} and 11.6 – 15.1 g $kg^{-1}$for the WL, AC, AM, NF and CT plots, respectively. Table 1 also shows that the variability of organic matter was least for the WL (CV = 7.5%). Alley maize gave the highest variability (CV = 10.8%). As with organic carbon, the aggregate stability as indicated by the MWD was far greater for the WL (MWD = 1.78 ± 0.01 mm) with the least variability (CV = 3.3%). Although the CT soil showed the least stability (1.31 ± 0.03 mm) and fairly high variability (CV = 8.3%), the variability of MWD in the NF system was the highest (CV = 9.1%). The variation in OC accumulation with depth in the soils is shown in Table 2. The OC content in the two soil profiles fell sharply from the A horizon to the B horizon. Similar to the OC content, the stability of soil aggregates was greatest at the surface and generally decreases with depth.

Generally, the range of OC values are characteristic of soils in the sub-humid tropics (Ahn, 1993). The higher accumulation of organic carbon in the woodlot may be attributed to the greater litter additions from within this farming system. Previous study on this soil by Dowuona et al. (1998) estimated that as much as 7 t $ha^{-1}$of litter is added per year to the woodlot system. Despite the fact that the soil under the NF is uncultivated, the rate of establishment of the secondary natural vegetation is slower than the *Leucaena* woodlot resulting in a lower supply of litter to the fallow soil (<4 t $ha^{-1}$of litter). The accumulation of organic matter in the A horizon and the depth gradient of OC content in the profiles confirm that these farming systems indeed influence organic carbon turnover in the soils.

Although the alley farms receive additional organic residues (<2 t ha^{-1}) from pruning of the *Leucaena* hedgerows, the soil OC content was lower than that of the WL soils. This may be attributed, on one hand, to the annual harvest of crops, and on the other, to the more frequent cultivation that improves soil aeration leading to faster organic matter decomposition. In the case of maize, for example, the annual harvest of the crop (ears comprising the cobs and grains) would lead to the removal of residues from the fields.

The stability of soil aggregates under the various farming systems may, in part, be controlled by organic matter content. A good correlation was established between MWD and OC content of the soils (Table 3).

Table 3. Relationship between mean weight diameter (MWD) and organic carbon of the soils

Land use system	Correlation coefficient (r)
Woodlot (WL)	0.69**
Cassava alley (AC)	0.62**
Maize alley (AM)	0.73**
Natural fallow (NF)	0.73**
Conventional tillage (CT)	0.76**

** = Significant at 1%.

For the woodlot, in particular, the relatively large accumulation of organic matter, canopy protection, binding action of roots and minimum tillage may account for the higher MWD values and the least variability in the stability of aggregates. Similarly, weaker aggregates of the CT could be attributed to frequent disturbance of the soil from cultivation, mechanical rupturing of aggregates and reduction in organic matter content. Long periods of cultivation preceding the fallow might have led to reduced cementing action of biotic life leading to weaker aggregates under the natural fallow system.

Spatial variability of soil properties

The correlograms for OC (Figure 1) show how this soil property is space dependent. It can be observed that the value of the correlation coefficient for the WL system was greater than zero up to k =5 (or 25 m) (Figure 1a). Using the $1/e$ criterion, the correlation length was determined to be k = 4 (or about 20.0 m). With respect to OC, our interpretation is that the patch of soil lying within 20 m can be considered to be homogeneous. This observation suggests that the effect of woodlot is not only to increase soil OC content but also to homogenise the soil in terms of this property. This apparently reflects the favourable conditions of the closed canopy, which adds uniform amounts of leaf litter to the whole plot. Furthermore, the low spatial variation and hence the more uniform OC contents of the WL soils may also be attributed to the relatively long fallow period with no disturbance of the soils under this farming system.

For the NF system, the correlation length was about one lag (5 m); nevertheless, there is some correlation until k = 2 (i.e. 10 m). It appears that the homogenising effect, while present, is proceeding at a slower pace than in the woodlot. On the other hand, there is a relatively greater spatial variation in soil organic carbon in the alley plots. Both AC and AM

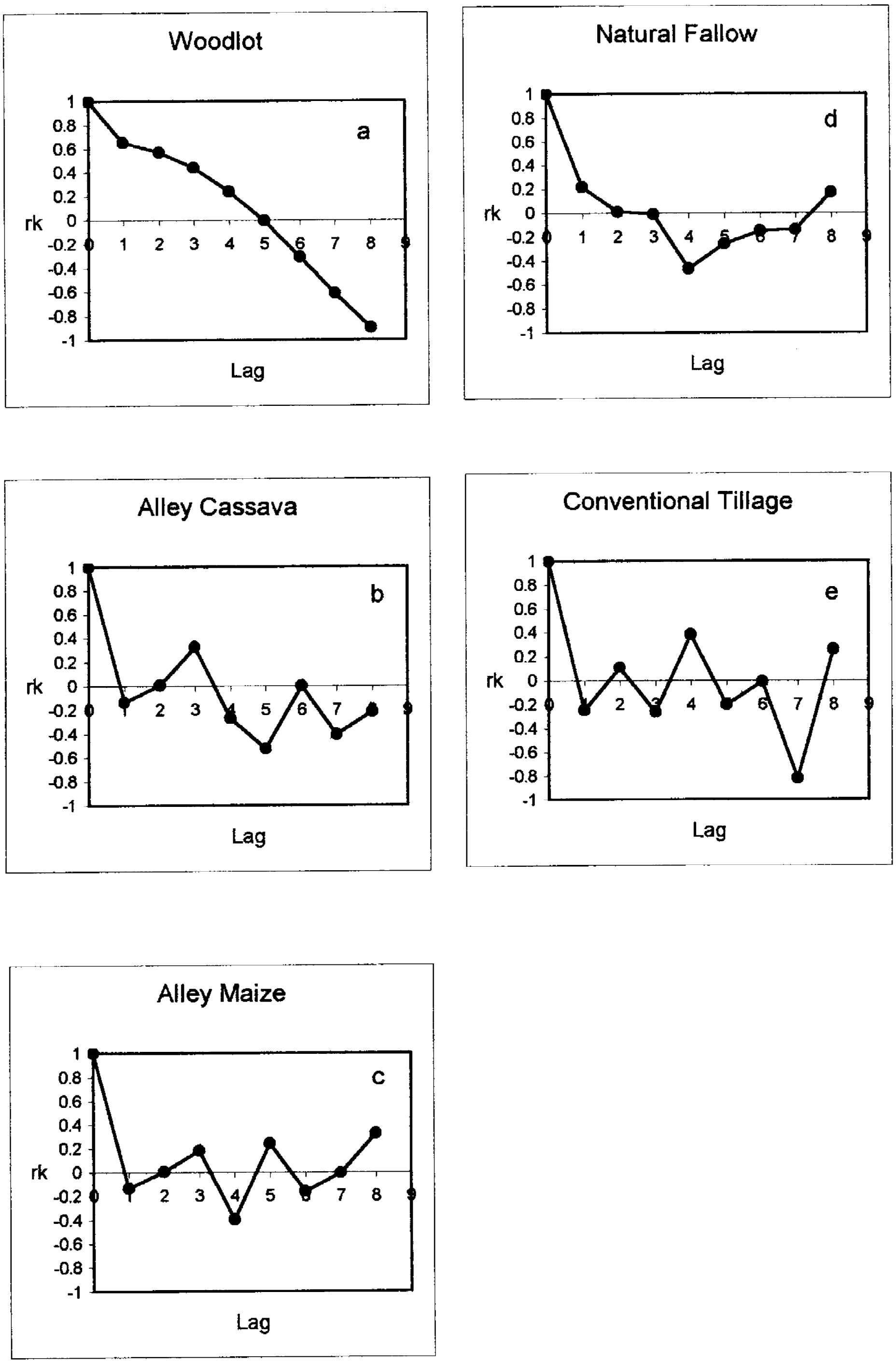

Figure 1. Correlograms of organic carbon content for the various farming systems.

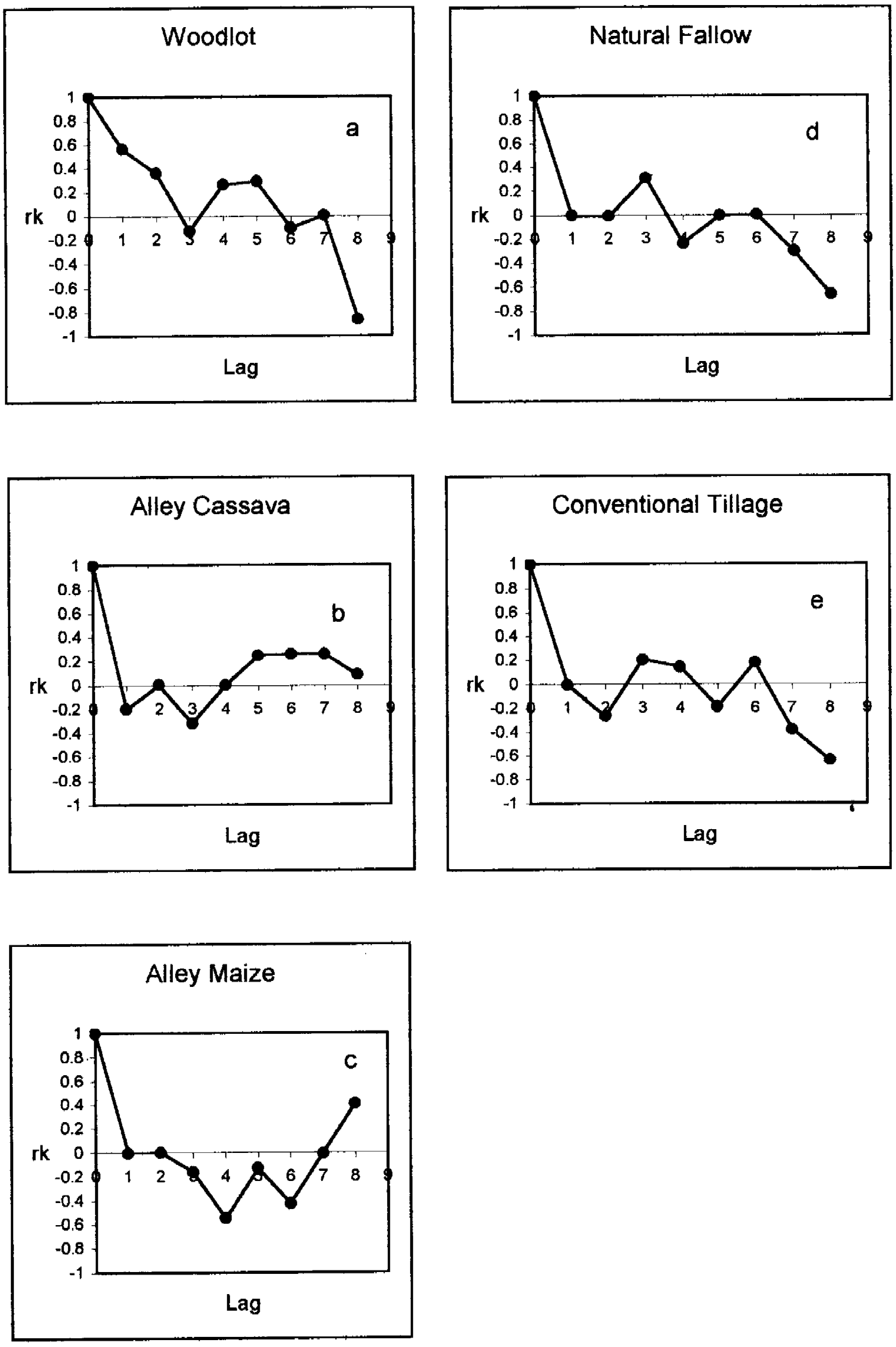

Figure 2. Correlograms of mean weight diameter for the various farming systems.

have correlation lengths less than one lag value (i.e. less than 5 m) suggesting less uniformity (Figure 1b, c). The distribution of OC in the soils under the alley system is, therefore, patchy. The spatial variability of OC for the NF and CT systems (Figure 1 d, e) are similar to that observed for the AC, having correlation lengths less than 5 m.

Continuous cultivation and harvesting of crops may have caused an increase in spatial variation and hence less uniformity of organic carbon additions under the alley plots. This is in accord with observations by Onofiok (1993) in other tropical soils. Cultivation might have resulted in different mineralisation rates at different points within these plots, culminating in the greater variability observed. Another possible reason for the non-uniformity of organic carbon could be the non-uniform return of organic residues to different parts of the plot through litter fall and plant exudates.

The spatial variation in the MWD values of the soils under the five farming systems is shown in Figure 2. The stability of aggregates under the WL, which had a correlation length of k = 2.5 (or 12.5 m) (Figure 2 a), is more uniform than that of the other farming systems (Figure 2 b, c, d, e). The uniformity in the MWD of the woodlot soils bears a spatial distribution pattern similar to the variation in organic matter content. As noted in the preceding sections and also in previous studies (Dowuona et al., 1998; Tete-Mensah et al., 1997), a close correlation exists between aggregate stability and OC content. The greater stability of aggregates and the small variability would allow for the development of good, uniform structure in the soils under the woodlot. This in turn would prevent erosion and improve the quality of the soil.

The MWD for the AC, AM, NF and CT was poorly related from point to point showing clearly the lack of uniformity within these farming systems. The correlation lengths were generally less than 5 m. Cultivation of the soils results in the destruction of soil structure and soil aggregates; the degree of cultivation is barely uniform throughout an entire field. This causes varying degrees of destruction of soil aggregates from one point to the other and may, in part, explain the non-uniformity of the stable soil aggregates under the alley systems.

It may be noted that even though our data for the determination of the spatial variability of the soil properties were obtained from unidirectional transects only, which may be interpreted as a limitation on a wide scale generality, the evidence from this study and previous ones (Atsivor, 1997; Dowuona et al., 1998, 2000; Tete-Mensah, 1993) confirm that woodlot systems reduce the variability of the properties more than the other farming systems. Furthermore, data on the modal profile will allow for extrapolation of information for efficient use and management of similar soils elsewhere in the tropics.

Extreme variability of soil properties within a field can lead to practical difficulties in soil management. For example, when a blanket fertiliser application rate is used in field operations, some portions of the field may receive an overdose of the nutrients while some other parts may still be deficient. Consequently, yield quality may be poor as the crops located at different parts of the field may mature at different rates. Even though new farming techniques such as precision farming are geared to remove the undesirable effects of soil variability, the cost of this appropriate technology is currently beyond the economic scope of the simple, small-scale tropical farmer. The major finding in this study is that establishment of woodlot as improved fallow is a simple farmer-oriented management tool that can be used to minimise the variability in properties of soils in a field and thus improve grain yield. This is supported by data obtained from a farmer's field where the grain yield of maize grown on this soil previously under *Leucaena* woodlot was 3.8 t ha^{-1} compared to 1.8 t ha^{-1} under a CT plot.

Conclusion

The paper assessed the variability of two important soil properties under five farming systems in the sub-humid zone. The woodlot accumulated the greatest amount of organic matter with better stability of soil aggregates, which makes this farming system better in reducing land degradation and thus improve soil quality. The conventionally tilled farming system had the least organic matter accumulation and the weakest structural aggregates. The shorter correlation lengths observed for MWD of soil aggregates in the majority of the farming systems suggest that soil structure takes a longer time to stabilise and homogenise. Conservation of soil structure, therefore, remains the greatest problem in soil productivity and provides the basis for further research. Information provided in this study may also be useful for efficient use and management of degraded soils in the sub-humid tropics.

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