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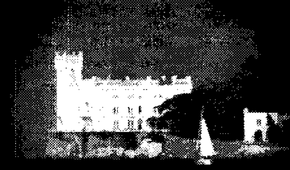

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THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

CARBON AND NITROGEN – THE KEY TO BIOLOGICAL ACTIVITY, DIVERSITY AND PRODUCTIVITY IN A HAPLIC ACRISOL

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Abstract

Soil organic matter is important because it impacts all soil quality functions. Much less information is available on the dynamics of the residual carbon and nitrogen content and their distribution in continuously cropped arable fields.

We described the values of the soil properties, pH, moisture content, organic carbon and total nitrogen considering them to be random variables. We treated their spatial variation as a function of the distance between observations within the study site, a continuously-cropped field dominated by Haplic Acrisols. We discussed the nature and structure of the modeled functions, the semivariograms, and interpreted these in the light of the potential of these soils to sustain agricultural productivity. At these sites there had been no conversion of natural forests to agriculture so the paper does not discuss soil carbon storage for either the regional or global storage.

All the properties studied showed spatial non-stationarity for the distances covered, indicating that the variance between pairs of observations increased as separating distances also increased. pH, moisture content and total nitrogen were fitted with the power model whereas the linear model best fitted organic carbon. Total nitrogen had the least nugget variance and pH the highest estimated exponent, α, from the power equations. The soils are highly variable in terms of input or return of organic residue to provide a sink for carbon and nitrogen and the breakdown of these materials as affected by pH, moisture availability and microorganisms.

INTRODUCTION

The organic matter content and hence the rate of decomposition in soils differ from place to place as a result of different management practices, the turnover time, substrate availability and activity of the soil biomass. The effect of organic matter on a soil can be dramatic, in that addition of organic matter can improve virtually almost all soil properties. A loose and more porous soil, lower bulk density, higher water-holding capacity, greater aggregation, increased aggregate stability, lower erodibility, greater soil fertility, increased CEC and others can be achieved.

The carbon:nitrogen (C:N) ratio in soil organic matter is important for two major reasons, namely, keen competition among micro-organisms for available soil N occurs when residues having a high C:N ratio are added to soils, and the C:N ratio is relatively constant in soils thus the maintenance of carbon and hence soil organic matter is constrained by the soil nitrogen level (Brady and Weil 2002). Since the C:N ratio of soils in a given region is reasonably constant, the level of soil nitrogen definitely influences the level of organic carbon and vice versa. Also, since a rather definite ratio (about 1:1.7) exists between the organic carbon and the soil humus, the amount of organic matter that can be maintained in any soil is largely dependent on the amount of organic nitrogen. Soil carbon stock is one on the indices of sustainable agriculture, for it affects storage and release of nutrient ions, buffer system for soil pH, nutrient carrier, and mobilization of phosphorus and improved soil structure.

There is a growing realization that soil degradation is the root cause of declining agricultural productivity in Sub-Saharan Africa (SSA) and that unless it is checked, many parts of the continent will suffer increasingly from food insecurity (World Bank 1996).

We investigated the long-term effects of continuous cultivation on the distribution of organic matter (organic carbon and organic nitrogen), with the view of elucidating the potential of these soils for sustainable land use and management strategies. Classical statistics and principles of geostatistics have been employed to unearth the spatial distribution of selected soil properties. The paper does not attempt to measure scales and intensity of degradation on these soils. Soils at the study site have been continuously cropped for nearly thirty years.

The Reference Soil Group of the Acrisols holds that these soils are characterized by accumulation of low activity clays in an argic subsurface horizon and by a low base saturation level. The formation of these soils has been conditioned by climate (sub-) humid tropics.

MATERIALS AND METHODS

Physical environment of the study site

The site covered the total environs of the teaching and research farm of the University of Cape Coast, Cape Coast in Ghana. The original vegetation on the site has very much been disturbed by farming, with the present cover consisting of stages of secondary vegetation. There are various species of shrubs and herbaceous plants, typical among them being *Cyperus rotundus*, *Portulaca oleracea* and extensive patches of *Panicum maximum*. The topography of the site is a gentle slope with deep, permeable, well-drained soils with a significant amount of topsoil. The parent rock materials from which the soil arises are known be sandstones, shales and conglomerates.

There are two seasons of rainfall, separated by a short dry period. The major rainfall season is from March to July whilst the minor season is from September to November. On the average, the site experiences between 900-1000 mm of rainfall per year. Annual temperatures are between 25-27 °C.

Soil sampling

Soil samples were taken from the 0-20 cm depth using a 10-cm long by 10-cm diameter bucket auger. Three random transects were laid across the entire study site, 525 m, 550 m and 675 m. Along these and at the boundaries of the entire study site, 160 soil samples were taken at staggered separating intervals of 2, 5 and 10 m. On the slopes, the lowest separating distance of 2 m was used in order to capture boundary differences. Samples were air-dried for 10 days, ground and screened through a 2-mm mesh sieve for laboratory analyses on the fine earth. The following parameters were investigated: pH, moisture content, organic carbon (OrgC) and total nitrogen (totN).

We measured pH using a digital pH metre in a 1:2.5 soil:water suspension. The suspension was stirred intermittently for 30 minutes after a glass electrode was inserted to record the pH (Thomas 1996). Organic carbon was by the wet oxidation method with normal $K_2Cr_2O_7$ with the aid of H_2SO_4 followed by determination of the excess chromic acid by titration with normal ammonium ferrous sulphate using diphenylamine indicator (Walkley and Black 1934). For total nitrogen, we followed the Kjeldahl procedure whereby samples were digested to convert the nitrogen into ammonium nitrogen with the subsequent liberation of the ammonium and titration with hydrochloric acid (Bremner and Mulvaney 1982). Moisture was by the gravimetric determination, whereby samples were oven-dried at 105 °C for 16 hours.

Summary statistics (descriptive statistics) and semivariogram analyses and modeling of spatial functions of the measured properties were performed in GENSTAT version 6.1. All data were assessed for normality. We assume in geostatistics that the data are realizations of a random process with uniform variance, the intrinsic hypothesis of stationarity (Journel and Huijbregts 1978). For any pair of random variables, those that are closer together are more likely to have similar values than those that are farther apart from each other and that neither the expectation of the process nor its semivariance are location dependent (i.e. stationary). A sample semivariogram, $\gamma(h)$, is computed as

$$\gamma(h) = \frac{1}{2(n-h)} \sum_{i=1}^{n} (Z_{xi+h} - Z_{xi})^2 \qquad (1)$$

where x_i and $x_i + h$ are sampling locations separated by a distance h, and Z_{xi} and Z_{xi+h} are measured values of the variable Z at the corresponding locations. Directional semivariograms were calculated in the north-south, east-west, northwest-southeast and northeast-southwest directions. There were no anisotropic variations and hence only the omni-directional semivariograms were considered, spanning a maximum lag of 200 m. The spatial variability of the different variables were then described in terms of the perceptible distance of spatial dependence (range), process variance (sill) and the spatially independent or random error (nugget) (Goovaerts 1997; Webster and Oliver 2001).

RESULTS AND DISCUSSION

Summary statistics of pH, moisture, orgC, totN and C:N ratio have been presented in Table 1. About 90% of the samples had pH values below 7.0. The soil pH varied from a minimum of 4.3 (extremely acid) to a maximum of 8.1 (moderately alkaline) (Smith 1962). The mean pH across the field was 6.0, an indication of medium acidity and an ideal medium for plant growth (Foth and Ellis 1997). The pH of a soil as an indicator of soil acidification is mainly dependent on the type of parent material and the level or extent of soil leaching at the site (Thomas 1996). Moisture content varied across the field between 0.89 and 3.13%, settling on a mean moisture content of 0.89%. Acrisols tend to have low biological activity and very little weatherable minerals left. The predominantly loamy sand or coarser textures might explain the low moisture contents of these soils (FAO 2002).

Organic carbon content was in the range of 0.01 – 4.40%. The mean was 1.17%. Nearly 96% of the soil samples (154 out of 160) had organic carbon contents less than 1.33%. This is acceptable for an average tropical soil (Landon 1991). The wide variation in the levels of organic carbon could be attributed to variable vegetation cover and manure additions over the years that the soils have been under cultivation. In addition to the above, vegetation or plant material may have been continuously removed for human and animal consumption with very little being returned to the land, oxidation processes and erosion activities. The average organic C in a number of catenas studied in Nigeria was 3.3% for the humid and forest zone containing more acid soils and 1.6% for the drier forest and savanna zones. Entisols, mainly found in the valley, had an average organic carbon content of 3.4% in the topsoil. For Ultisols, Alfisols, Inceptisols and Mollisols, the average was in the range 2.2-2.4%. Soils of the top crests tended to have a higher C content, 3.3%, than those of the slopes, 2.2%. Lowest organic carbon content was found between pH 5.0-6.0. Below a pH of 5.0, reduced biological activity and the increased mobilization of toxic cations may reduce the decomposition rates of organic matter. Lime applications are often recommended to increase soil pH to the range 5.0-6.0. Liming may stimulate breakdown of organic matter and thus contribute to crop nutrition, but possibly at the cost of maintaining the soil organic matter content. An increase in organic C content above pH 5.5 may be associated with a different mineralogy.

Soil organic carbon has been found not to differ widely between low and high activity clay soils, however allophanic soils (with large amounts of amorphous or crypto-crystallized minerals) exhibited higher soil organic carbon levels under similar climatic and land use conditions. Other variations of soil organic matter in allophanic soils could be as a result of very stable humus-Al, Fe-complexes, which may be protected from bacteria and enzymes in micro-aggregates.

Long-term field trials have shown a relation between declining crop yields, loss of soil cover and reduced levels of organic carbon. There is also evidence to suggest that application of inorganic fertilizers will not increase yields to the high levels obtained before the reduction in soil organic matter (Chinere et al. 1990).

Nitrogen varied between 0.02 and 0.41% across the field, with a mean of 0.11%. This observation is in line with several other studies that have quoted nitrogen content of the subsoil from 0.02% to more than 2.5% in peat. Similar observations have been found for the ploughed layer of a majority of uncultivated soils (Tisdale et al. 1993). The continuous ploughing and cultivation have rendered the soils impoverished. The level of nitrogen in a given soil could vary widely depending on the season and the cultivation history, complete removal of vegetation, losses through volatilization and denitrification. The situation is even worse where there is continuous cropping of non-leguminous species (Mengel 1982). Nearly 84% of the soil samples have nitrogen levels between 0.01-0.20%, which Hesse (1971) classified as low to very low. The implication with this observation is that sooner or later, the nitrogen in the soil can no longer support plant growth with the consequences being that there would be reduced productivity and other nitrogen-related deficiency symptoms. With the right cultivation practices, a medium to high level of nitrogen can be maintained, supported by the fact that about 16% of the soil samples have nitrogen levels between 0.21-0.41%. Carbon:Nitrogen ratio varied significantly. For 43% of the soils, C:N ratio was between 0.6 and 10 and 49% of the samples showed ratios between 11 and 20. The mean C:N ratio was 12:1. Organic matter contains 50-58% C, giving a C/N ratio ranging between 9 and 12 (Tisdale et al. 1993). Therefore the incorporation into the soil of residues with high nitrogen content can reduce this ratio. Undecomposed straw residues tend to increase the ratio as in this case, whilst legume residues high in nitrogen tend to reduce it. Brady and Weil (2002) found the C:N ratio in the organic matter of the furrow slice (upper 15 cm) of arable soils to fall between 8:1 and 15:1, the median being between 10:1 and 12:1. The 95% confidence interval for C:N ratio was 10:1 to 14:1 (Table 1, Figure 1).

In tropical soils, however, this ratio could be higher due to high temperatures. The fluctuations are basically due to incorporation into the soil of residues with varying nitrogen content. The implication of a high ratio is that there will be keen competition among micro-organisms for available soil nitrogen. Prospective farmers at this site would need to think of either adding chemical or organic nitrogen-based fertilizers to ensure that plants have enough nitrogen for development.
Table 1 also shows that all the properties studied at the site had very slight positive skewness with the exception of C:N ratio which was strongly positively skewed and pH very slight negative skewness. None of the parameters was transformed. Similar trend was found for kurtosis, with C:N ratio recording the highest kurtosis and pH, a negative kurtosis. C:N ratio was not included in the analysis for spatial structures.

Table 2 presents parameters of omni directional semivariogram models, namely the range, nugget and slope and the percentage variance accounted for in the linear and non-linear regression analyses of the calculations of the semivariograms. Modeled functions of pH (Figure 2), moisture content (Figure 3) and total nitrogen (Figure 5), were fitted with the power model (equation 3) whilst that of organic carbon (Figure 4) was fitted with a linear model (equation 2). All the properties studied showed unbounded or non-transitional semivariograms, which meant that the variance of all observations within the domain was not constant. As the lag distance increased, the semi-variance, $\gamma(h)$, continued to increase. For small values of h, however, the power models for pH, moisture and total nitrogen can also be approximated with the linear model, where $\alpha = 1$ (equation 3).

Linear model $\quad \gamma(h) = C_o + mh \qquad h \geq 0 \qquad$ (2)

Power model $\quad \gamma(h) = C_o + mh^{\alpha} \qquad h \geq 0; \qquad 1 < \alpha < 2 \qquad$ (3)

The calculated values of the semivariance extrapolate to a value called the nugget variance, rather than to the origin. Nugget variance ranged from 0.005946 for total nitrogen, to 0.277 for pH. Moisture content and organic carbon recorded 0.1873 and 0.2354 respectively. The nugget variance is either associated with spatially dependent variation occurring over smaller distances than the smallest sampling interval or due to measurement errors, the latter being the major contributor. The exponents estimated for the models were 1.991, 1.812 and 1.923 for pH, moisture and total nitrogen respectively. Standard errors of the exponents were between 0.245 and 0.447.

Soil organic matter plays an important role in determining the fertility and productivity of soils. This may be especially true in tropical areas where nutrient-poor, highly-weathered soils are often managed with few external inputs. Moreover, from a global change perspective, land use management influences the ability of soils to serve as both a source and a sink of soil organic matter and nutrients.

In a broadest sense, soil organic matter dynamics are driven by climate, soil type (mineralogy) and land use management. These factors interact to determine the physical, chemical and biological controls on soil organic matter. Together, they regulate the quality and quantity of soil organic matter inputs, the composition and activity of decomposer communities and rates of soil organic matter loss by mineralization, leaching and erosion. Decomposition of organic matter may take several months to several years to complete. In tropical regions, the whole process is quite quick because moist conditions and high temperatures enhance biological activity.

Numerous studies describing the relationship between clay (or clay + silt) content and soil organic matter have shown that clay (or clay + silt) content is a relatively important determinant of soil organic matter levels in low activity clay soils. This relationship (Feller et al. 1991a) appears to hold equally well for cultivated soils as for those under native vegetation in situations covering a wide range of mean annual precipitation (600-3000 mm yr^{-1}). Therefore, the low organic matter content of sandy soils of West Africa may be attributed to their low clay content (<20%) in addition to management associated factors such as overgrazing and intensive farming.

The structure of a semivariogram is the shape and nature of the curve for values greater than the nugget variance. The semivariogram does not describe magnitudes of observations but rather deals exclusively with differences – pairs of observations subtracted from each other. The soil properties studied manifested a spatial variance that is unbounded signaling that the soils are highly variable in terms of input or return of organic residue to provide a sink for carbon and nitrogen and secondly in the breakdown of these materials as effected by pH, moisture availability and microorganisms. These properties showed spatial non-stationarity for the distance considered. These soils with awful amounts of low activity clays would require improved soil productivity techniques incorporation of organic manures, green manuring, residue incorporation, mulch tillage, zero tillage and legume-based crop rotations to rejuvenate the soil of its carbon and nitrogen stocks.

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Table 1 Summary statistics for soil properties studied

Parameter	pH (pH units)	Moisture (%)	Organic Carbon (%)	Total Nitrogen (%)	C:N[ab]
Mean	6.0	0.89	1.17	0.11	12
Minimum	4.3	0.13	0.01	0.02	0.4
Maximum	8.1	3.13	4.40	0.41	110
Standard deviation	0.76	0.56	0.76	0.08	10.61
Standard error	0.06	0.04	0.06	0.01	0.84
CV (%)	12.7	63.2	64.9	70.5	88.4
Skewness	-0.06	1.35	1.06	1.08	6.39
Kurtosis	-0.49	2.28	1.55	0.85	51.01

[a]Carbon:Nitrogen ratio [b]Confidence level (95%) = 10-14

Table 2 Characteristics of semivariogram models for the soil properties studied

Parameter	Model	Exponent (α)	Sill	Nugget	Slope	% Variance[d]
pH	Power	1.991 (0.447)[a]	-	0.277[b]	0.924E-05	96.1
Moisture	Power	1.812 (0.245)[a]	-	0.1873[c]	0.230E-04	98.6
Organic Carbon	Linear	-	-	0.2354[c]	0.265E-02	88.4
Total Nitrogen	Power	1.923 (0.284)[a]	-	0.005946[c]	0.473E-06	98.3

[a]standard error of estimated exponent, α, in the power model

[b] = [pH units]^2

[c] = [%]^2

[d]percentage variance accounted for in the linear and non-linear regression analyses

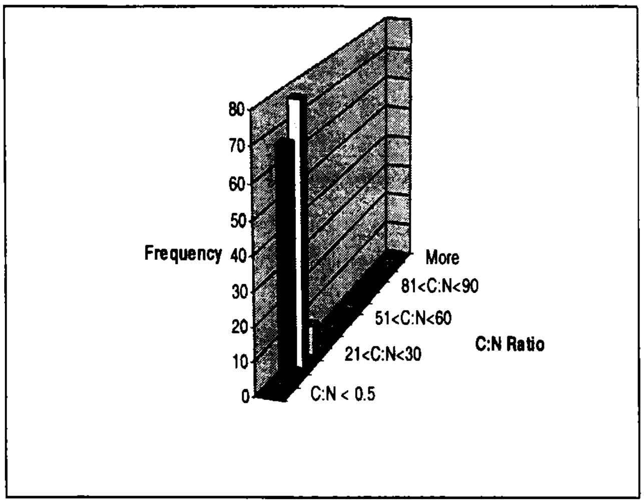

Figure 1 Histogram of carbon:nitrogen ratio

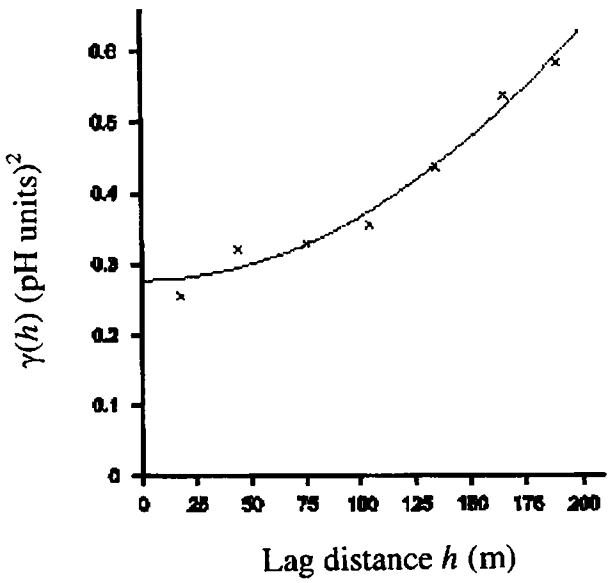

Figure 2 Semivariogram for pH

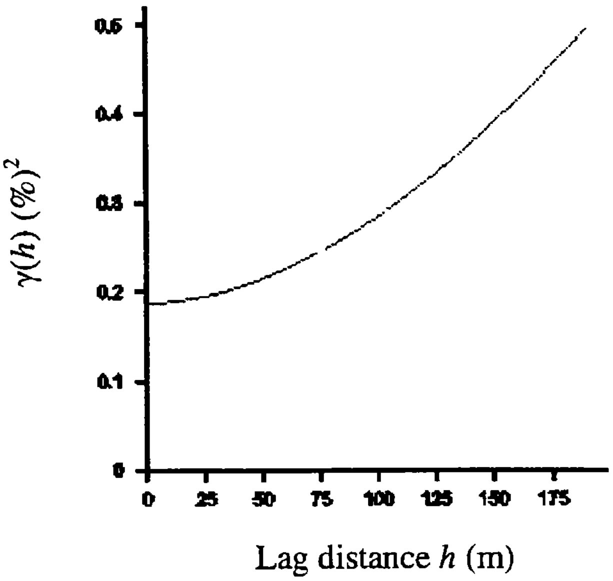

Figure 3 Semivariogram for moisture content

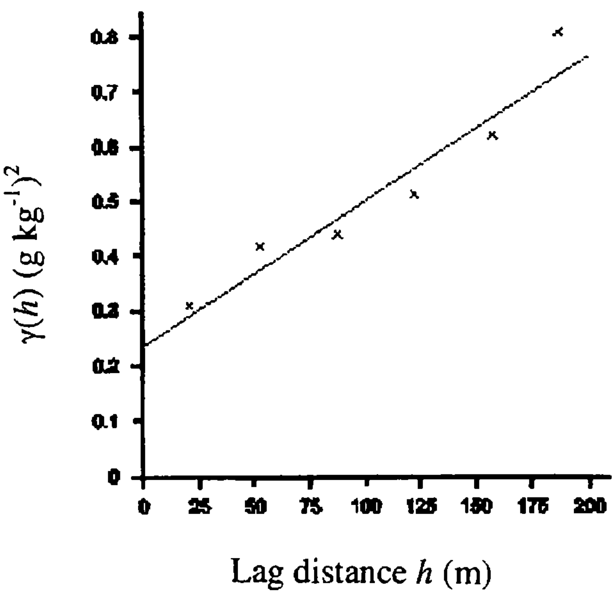

Figure 4 Semivariogram for organic carbon

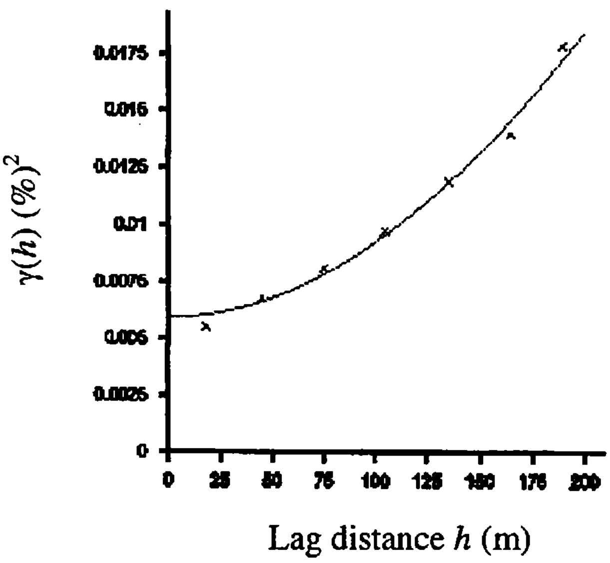

Figure 5 Semivariogram for total nitrogen