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Assessment of management strategies for sustainable soil productivity in a West African savanna

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Abstract

Declining soil fertility in West African savanna has caused increasing reliance on inorganic fertilizers to maintain soil fertility and productivity. A long-term field experiment was initiated in 1949 to determine the best combination of farmyard manure, mainly cow dung manure, with inorganic fertilizers (NPK) that would maintain soil fertility and productivity. In this study, we determined the changes in organic carbon (OC), nitrogen (N), effective cation exchange capacity (ECEC) of the soils, and the electrical conductivity (EC) and ionic strength (I) of soil solution from four treatment plots: control plot; NPK-fertilized plot; FYM-plot and NPK + FYM-plot after 50 years of continuous cultivation. Mass balance calculations indicated that the control plot and NPK-plot incurred a 45 % loss OC on the surface horizons, but these losses were reduced to 21 % for FYM and 14 % for FYM + NPK fertilized plots. Similar trend was observed for N in the soils. Application of NPK reduced CEC declined by 35 % in the surface horizons in contrast to net gains made in the other plots. Averaged across the horizons, applications of FYM and FYM+NPK increased CEC by about 62 % and 60 % respectively. The ionic strength I of soil water extracts in FYM- and FYM + NPK-plots, which is an index of dissolved nutrient cations and anions in soil solution, was on par with the uncultivated site in Ap horizon. In Bt horizon, applications of FYM and FYM + NPK increased I twofold suggesting considerable leaching of cations and anions from the surface horizon. The present data suggest that maintenance of inherentl fertility status of these soils can be best achieved with FYM in combination with NPK; but long-term applications of NPK without FYM had deleterious effect on OC and CEC. Future research must focus on suitable management techniques involving the combination of inorganic fertilizers with organic manure or locally-available organic residue for the maintenance of long-term soil soil fertility and productivity.

Keywords: Carbon, N, CEC, fertility management, sustainability

Introduction

Increasing population pressure in West African savanna has provoked an urgent need to find appropriate management practices to maintain long-term soil fertility and productivity if food and fibre production in the region is not to be seriously undermined. Increasing population pressure leads to rapid soil degradation (Lal, 1995; Eden, 1996).

Soil scientists, ecologists and geographers are unanimous that soil is the most important resource component in sustainable agricultural prodictivity and development (Hartemink, 1998). Development of suitable soil management technologies is a global challenge for sustainable agricultural productivity and development. Although the concept of ‘sustainability’ might not lend itself to a simple definition, it is generally agreed that sustainable soil / land management must address combined production and conservation of natural resources, in our context, soil resources, on which agricultural production acutely depends (Hartemink, 1998).

Maintenance of long-term fertility and productivity of strongly weathered and poorly buffered savanna soils is a major challenge facing the region whose economy depends, to a large extent, on agriculture. Complete reliance on inorganic fertilizers is not an attractive option because of the large subsidies and foreign exchange component required for fertilizer importation (Ogunfowora, 1996). In addition, long-term applications of inorganic fertilizers have a stressful effect on savanna ecosystems by seriously impairing soil 'health'. Reduced cation exchange capacity, cationic balance, organic C and microbial C, N and P on surface horizons are associated with long-term inorganic fertilizer applications (Agbenin and Goladi, 1997a; Goladi and Agbenin, 1997).

The questions that must be addressed are: i. how can we judiciously use inorganic fertilizers to improve soil fertility and productivity of strongly weathered soils without endangering the ecosystem? ii. Are there alternative soil management technologies in the region? While conceding that inorganic fertilizers are indispensable to improving the fertility and productivity of these nutrient-poor soils for purposes of increasing food and fibre production in the region, researchers must also examine the long-term consequences inorganic fertilizers on strongly weathered and poorly-buffered soils, and proffer methods of mitigating these dangers.

A proper assessment of soil management practices for sustainable soil productivity requires long-term data (Greenland, 1994) which are rarely available in Sub-Sahara Africa since agricultural research in the region is a fairly recent development. Because there are no universal indicators of sustainability, key variables have to be chosen from an agroecosystem to assess its sustainabilty based on the constraints to productivity in that ecosystem. Even if universal indicators can be found, the temporal and spatial boundaries will still need to be defined (Hartemink, 1998) because of the wide differences in soil cultivation methods and husbandry. In this study, we chose organic carbon (OC), nitrogen (N), cation exchange capacity (CEC), and the ionic strength *(I)* of soil solution of a savanna soil under different management practices to assess sustainable soil productivity. Others might like to add crop yield, but this is an unstable index because crop yields are significantly affected by other exogeneous variables which are unrelated to soil condition, such as diseases, pests, weeds, planting / sowing dates, plant population, variety and microclimates. In this study, we compared key soil fertility and productivity indicators in a cultivated savanna soil with an uncultivated soil chosen as a reference condition. Our objective was to determine the management practice which has the least degradative effect on soil fertility status after 50 years of continuous cultivation and systematic fertilization practices.

Materials and methods

The soils for this study were chosen from the long-term field plots at Samaru: 11^o11'N 7^o38'E in the Northern Guinea Savanna of Nigeria. The experiment was extablished in 1949 in a Kaolinitic, Kanhaplic Haplustalf (Moberg and Esu, 1991). The experimental field has three levels each of farmyard manure (FYM) as cow dung, N, P and K applied in all possible combinations. Details of experimental design were previously described by Agbenin and Goladi (1997b) and Goladi and Agbenin (1997).

Four field plots which are representative of common management practices were chosen for detailed profile studies. The assessment of soil fertility changes was carried out for three genetic horizons, Ap, BA and Bt, to account for possible soil nutrient mobilization and translocation between horizons over the years of cultivation and fertilization. The four plots selected were: check-plot receiving neither inorganic fertilizers nor FYM; NPK-plot fertilized with NPK, FYM-plot receiving cow dung manure; and NPK+FYM receiving both NPK and cow dung. Application rates were 48-135 kg N ha^{-1} yr^{-1}, 18-54 kg P ha^{-1} yr^{-1}, 29-58 kg K ha^{-1}

yr^{-1} and 5 t FYM ha^{-1} yr^{-1}. However, between 1996 and 1998, these treatments were not applied but the field was cultivated. An uncultivated adjacent site chosen as a reference condition was also sampled. The soils were air-dried and screened to pass through 2-mm sieve for physico-chemical analyses.

Soil analysis
Organic carbon status of the soil was determined by C and N Analyzer (CHN Rapid, Frühe Heraeus, Hanau, Germany). Cation exchange capacity of the soils was determined as the summation of exchangeable cations and exchange acidity. Exchangaeble bases were displaced with 1N NH_4-acetate and the cations were determined by atomic absorption spectroscopy, while the exchangeable acidity was displaced by 1N KCl and titrated with 0.1 N NaOH to the first permanent end point using phenolphthalein indicator (Thomas, 1982).
The soil ionic strength was estimated from elelectrical conducticity measurement. The EC of a soil saturation extract was determined by a portable pH and conductivity meter (HANDYLAB 2: Schott Geräte, Holfheim, Germany). Electriccal conductivity was converted to ionic strength *(I)* by employing the Marion-Babcock equation (Sposito, 1989) given as follows:

$$\log I = 1.159 + 1.009 \log (\mathrm{EC}) \qquad \text{(Eq. 1)}$$

Dissolved N (NH_4^+-N + NO_3^--N) was determined from the soil saturation after filtration. The NH_4^+-N + NO_3^--N in the extracts were measured with an Auto-N Analyzer (TRAACS 800: Bran and Luebbe, Norderstedt Hamburg, Germany).
To assess the impact of cultivation and management on the changes in trace elements, some references against which the measured concentrations and amounts of C, N, soluble N and CEC can be compared have to be established. For this purpose, the concentrations and amounts in an adjacent uncultivated site was chosen as the main reference condition.
Soil scientists contend that nutrient changes in soils evaluated by concentrations in a cultivated soil *visa viz* an uncultivated soil might be misleading because of the effect of cultivation on bulk density changes. Element concentration in a soil horizon is affected by cultivation because of changing bulk density, and consequently soil mass. The mass of a C, N and CEC on an area-basis was calculated for i. Ap horizon and ii. the entire profile to accomodate possible differences in bulk density, and to compensate for the dilution effect of high soil mass on elemental concentrations. The bulk densities of the soils were determined by the core method described by Blake and Hartge (1986).

Results and discussion

Carbon, N and CEC status
There were management-induced changes in the concentration of OC in the soils. Continuous cultivation without soil amendment (check-plot) and NPK fertilization had lower organic matter content than the uncultivated site in Ap horizons of the soil (Table 1). Addition of FYM and FYM+NPK maintained OC on a statstical par with the native. However, the tendency of higher OC in the native than all other treatments in the Ap horizon is attributable to rapid oxidation or decomposition of litter and crop residue due to tillage (Agbenin and Goladi, 1997a; Agbenin, 1998). Below the Ap horizon, the differences between treatments were not significant. Averaged across horizons, the NPK+FYM fertilized plot maintained OC levels approaching that of the native while NPK-fertilized plot had consistently low OC concentration (Table 1). The effect of management on OC is most evident on Ap horizon, and to a lesser extent, on BA horizon.

Table 1. Distribution of organic carbon and total nitrogen in three horizons of a savanna soil after 50 years of continuous cultivation

Treatment / landuse	Ap	BA	Bt	Weighted mean
Organic C (g kg^{-1})				
Check	3.6b	2.0bc	1.4b	2.1c
NPK	3.6b	1.7c	1.1b	1.6c
FYM	5.2ab	1.6c	1.2b	1.9c
FYM + NPK	5.7a	2.6ab	2.0a	2.8b
Native	7.2a	3.0a	1.8a	4.0a
Total N (mg kg^{-1})				
Check	310cd	223ab	163bc	216c
NPK	297d	217ab	130c	178c
FYM	437bc	183b	153bc	206c
FYM + NPK	530ab	287a	240a	303b
Native	580a	283a	187b	347a

Means followed by a common letter are not significant as determined by Tukey’s Honesty test of difference (HSD) at 5 % level of probability.

As would be expected the trend in N distribution paralleled OC distribution (Table 1) probably reflecting the definite stoichiometric relationship between C and N in soil organic matter (McGill and Cole, 1981). The check-plot and NPK-plot had significantly lower N content than the uncultivated site in Ap horizons of the soil (Table 1). Addition of FYM and maintained N on a statstical par with FYM+NPK-plot. Similarly, FYM+NPK-plot was on a stastical par with the native (Table 1). Despite annual input of N fertilizer in the NPK plot, it had the lowest concentration of N in Ap horizon and in the entire solum compared to other treatments. Averaged across the horizons, the NPK+FYM fertilized plot maintained N levels approaching that of the native while NPK-fertilized plot had the lowest N concentration (Table 1). Although not shown, C:N ratios were between 10 and 13 indicating no apparent differences in organic matter quality and the degree of humification.

The low amounts of total N in NPK-plot might be due to rapid crop uptake and leaching because of higher solubility and availability than in FYM-plot or in FYM+NPK-plot consistent with the disribution of soluble N (NH_4^+-N + NO_3^--N) in the profile (Table 2) and the N partition coefficients k_N (Table 2). In contrast to total N, the NPK-plot had more soluble N than other treatments. However, cultivation depleted soluble N compared to an uncultivated site which had 2-3 times more soluble N than the treatments because of crop uptake and export from the field. Nitrogen partition coefficients were significantly higher in FYM and FYM+NPK plots than other treatments suggesting that addition of organic manure could have caused some N immobilization or retention as NH_4^+-N in cation exchange sites. Therefore, the relatively low k_N of the NPK-plot is most probably related to high solubility of NPK fertilizer compared to FYM. Farmyard manure could potentially promote N immobilization when NPK fertilizer is combined with it depending on its initial C:N ratio. The combination of NPK fertilizer and FYM with high C content might be an effective mechanism for curtailing the leaching of NO_3^- -N applied as nitrogeneous fertilizers.

Table 2. Distribution of soluble N (NH_4^+-N + NO_3^- -N) and N partition coefficient k_N in the soil horizons after 50 years of continuous cultivation

Treatment / landuse	Ap	BA	Bt	Weighted mean
Soluble N (mg kg^{-1})				
Check	3.9b	2.8c	3.5b	3.4b
NPK	4,5b	3.6b	3.2b	3.5b
FYM	3.7b	2.5c	2.6c	2.7c
FYM + NPK	3.8b	3.0bc	2.3cc	2.7c
Native	11.0a	5.7a	4.5a	7.1a
Partition coeff. k_N				
Check	77c	77b	48bc	61b
NPK	67cd	59cd	40c	47c
FYM	125b	71bc	59b	68b
FYM + NPK	143a	91a	100a	105a
Native	53d	50d	42c	47c

Means followed by a common letter are not significant as determined by Tukey’s Honesty test of difference (HSD) at 5 % level of probability

Cation exchange capacity increased from Ap to Bt horizon (Table 3), but in Ap horizon NPK application significantly decreased CEC, indicating clearly that long-term application of NPK has a negative impact on nutrient cation storage capcity of savanna soils. The degradative effect of NPK fertilizers on soil CEC might be due to soil acidification previously reported by Goladi and Agbenin (1997); the effect of which could lead to the transformation of high-activity silicate clays to low-activity clays.

Table 3. Distribution of cation exchange capacity (CEC) and ionic strength *I* in the soil horizons after 50 years of continuous cultivation

Treatment / landuse	Ap	BA	Bt	Weighted mean
CEC (mmol$_c$ kg^{-1})				
Check	39.1a	82.2ab	86.6c	74.3bc
NPK	22.4b	75.8b	75.1d	67.9c
FYM	39.1a	97.4a	127a	103a
FYM + NPK	47.1a	86.8ab	108b	93.8ab
Native	38.2a	81.6ab	84.5c	67.6c
***I* (mmol$_c$ dm^{-3})**				
Check	33b	36c	30d	33c
NPK	36b	54ab	70b	61b
FYM	55a	48bc	66bc	57b
FYM + NPK	54a	63a	164a	130a
Native	48ab	42bc	36cd	42c

Means followed by a common letter are not significant as determined by Tukey’s Honesty test of difference (HSD) at 5 % level of probability

The tendency of CEC in Ap horizon of the check-plot to be statistically on par with the native suggests resilience of savanna soils to rapid degradation, while the significantly high CEC of the FYM- and FYM+NPK-fertilized plots are attributable to extra cation exchange sites conferred on the soil by OM increases in these plots. Jones (1973) reported that over 80 % of CEC of savanna soils is due to soil OM consistent with the significant correlation between CEC and OC reported for this field by Goladi and Agbenin (1997). Thus, the low CEC of the NPK-plot could be partly explained by its low OM.

The impact of management on soil ionic strength, *I*, an index of the intensity of dissolved ions in e soil solution (Table 3) indicated that FYM- and NPK+FYM-plots had more dissolved nutrient ions in soil solution than NPK and check-plot in the Ap horizon. However, averaged across the horizons the ionic strength of the soil solution increased in the order FYM+NPK > NPK > FYM > native > check, reflecting increasing nutrient input through fertilization. In the NPK- and FYM+NPK-plots, *I* increased with soil depth suggesting leaching of nutrient ions and accumulation in the subsoil. It would appear, therefore, that either nutrient inputs in these plots exceeded crop requirement or lack of synchronization of fertilization and mineralization with peak crop nutrient demands.

Impact of management on gains and losses of C, N and CEC

Masses of C, N and CEC per unit area normalized to the native site, chosen as a reference condition, were calculated. No attempt was made to determine the statistical significance of the losses / gains of C, N and CEC. Doing so requires that an *apriori* level of significance be chosen. Several investigators have actually expressed misgivings on the importance of statistical powers in studies of conservation of natural resources. Peterman (1990) and recently Pennock and van Kessel (1997) contended that in environmental and conservation studies, the practical consequences of failure to detect a difference (type II error) which indeed occurred in nature might be much more dire than the consequences of detecting a difference which did not occur in nature (type I error). Thus, we chose to express the net losses / gains of C, N and CEC in simple percentages.

The area-based changes represent the total amounts of C, N and CEC gained or lost which can be directly attributed to management history or land use. The losses / gains could have come from management-induced erosion, leaching, crop uptake, OM mineralization and nutrient input and output from the field. Continuous cultivation without fertilization reduced C by 45% and N by 41 % in Ap horizon (Table 4). Similarly, the application of NPK caused 45 % reduction in C and 44 % in N in the Ap horizon. These losses occurred throughout the entire solum (Table 4).

Table 4. Direct effect of cultivation on the mass balance of C, N and CEC in a savanna soil after 50 years of continuous cultivation

Treatment / landuse	Ap	BA	Bt	Weighted mean
OC (kg m^{-2})				
Check	1.2	-45	2.9	-44
NPK	1.2	-45	2.3	-56
FYM	1.7	-21	3.1	-39
FYM + NPK	1.9	-14	4.1	-20
Native	2.2	--	5.2	--
Total N (kg m^{-2})				
Check	102	-41	309	-33
NPK	97	-44	253	-44
FYM	143	-17	335	-27
FYM + NPK	173	0	462	0.9
Native	173	--	458	--
CEC (mol m^{-2})				
Check	12.8	12	125	19
NPK	7.4	-35	109	4
FYM	12.8	12	170	62
FYM + NPK	15.4	35	168	60
Native	11.4	--	105	--

Application of FYM and FYM+NPK tended to mitigate these losses in Ap horizon even though considerable losses of C still occurred in the entire solum with respect to FYM (Table 5). As previously alluded to, the comparable losses of C and N is the result of the definite stoichiometric relationships between C and N in SOM through C-N bond linkage (McGill and Cole, 1981; Agbenin and Goladi, 1997a). The most effective management against losses of C and N after five decades of continuous cultivation appeared to be FYM+NPK and FYM fertilization consistent with previous observations in this field (Bache and Heathcothe, 1969; Goladi and Agbenin, 1997).

Of interest in this study is the effect of management history on the gains and losses of CEC. Fertilization with NPK had the most deleterious effect on CEC (Table 4) in both the Ap horizon and the entire profile. Application of NPK reduced CEC by 35 % in the surface horizon and this contrasts with 12 % increase in CEC in the check- and FYM-plots, and the 35 % increase in FYM+NPK-plot. Averaged across the horizons, CEC increased by over 60 % in FYM and FYM+NPK fertilized plots in contrast to just 4 % in the NPK-plot. The degradative effect of NPK fertilization on CEC and OC clearly suggests that it is not a sustainable management practice for this soil contrary to the view that inorganic fertilizers can sustain soil productivity on long-term basis in the region (Juo and Kang, 1989). The degradative effect of NPK fertilization on soil CEC appeared to result from induced soil acidity probably because of the increased demands for basic nutrient cations due to vigorous crop growth and relatively high yields. After 45 years, Goladi and Agbenin (1997) found that pH = 3.8 in NPK fertilized plot in contrast to pH 4.8-5.1 in the other plots. The high net gains of CEC in plots fertilized with FYM and FYM+NPK would imply that organic manure especially crop residue and farmyard manure incorporation along with inorganic fertilization represents an important management strategy for sustainable soil productivity in the region.

Conclusions

Based on our indicators of sustainability, soil degradation in the savanna cannot be reversed by inorganic fertilization. Indeed it might facilitate the rate of degradation. Of all the management practices, NPK fertilization seemed to have the most deleterious effect on the soil.

Applications of FYM and FYM + NPK significantly enhanced the soil nutrient storage capacity evidenced by improvement in CEC. However, the the phenomenal increases in *I* in Bt horizon of FYM +NPK-plot suggested considerable leaching of nutrient ions from the surface. The combined treatment levels would have greatly exceeded crop requirements. The high losses of OC and CEC in NPK-fertilized plot indicated that this management strategy is not sustainable in contrast to the use FYM or better still combined NPK and FYM applications. However, the level of FYM+NPK has to be carefully determined to avoid groundwater pollution through leaching evidenced by the high electrical conductivity and ionic strength of soil extracts from this plot.

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References

Agbenin, J.O. (1998). Quantifying soil fertility changes and degradation induced by cultivation techniques in the Nigerian savanna. Advances in Geoecology 31, pp 435-441.

Agbenin, J.O., Goladi, J.T. (1997a). Carbon, nitrogen and phosphorus dynanics under continuous cultivation as influenced by farmyard manure and inorgani fertilizers in the savanna of northern Nigeria. Agriculture, Ecosystems and Environment 63, pp. 17-24.

Agbenin, J.O., Goladi, J.T. (1997b). Long-term soil fertility trend in the savanna as influenced by farmyard manure and inorganic fertilizer. In: Soil Fertility Management in West African Landuse Systems sysytems In: Renard, G, Neef, A, Becker, K and von Oppen, M (eds). Magraf Verlag, Weikersheim, Germany. pp. 21-29.

Bache, B.W., Heathcote, R.G. (1969). Long-term effects of fertilizers and manures on soil and leaves of cotton. Experimental Agriculture 5, pp. 241-247.

Blake, G.R., Hartge, K.H. (1986). Bulk density. In: A. Klute (ed.), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, American Society of Agronomy, Madison, Wisconsin, pp. 363-377.

Eden, M.J. (1996). Land degradation: environmental, social and policy issues. In: Land degradation in the tropics- Environmental and policy issues (Eden, M.J., Parry J.T. eds), Printers, London pp. 3-18.

Goladi, J.T., Agbenin, J.O. (1997). The cation exchange properties, the microbial biomss carbon, nitrogen and phosphorus as influenced by inorganic fertilizers and organic manure. Journal of the Science of Food and Agriculture 75, pp. 412-418.

Greenland, D.J. (1994). Soil science and sustainable land management. In: Soil science and sustainable land management in the tropics (Syers, J.K., Rimmer, D.L. eds.), CAB International, Walling Ford, pp. 1-15.

Hartemink, A.E. (1998). Soil chemical and physical properties as indicators of sustaianble land management under sugar cane in Papua New Guinea. Geoderma 85, pp. 283-306.

Juo, A.S.R., Kang, B.T. (1989). Nutrient effects of modification of shifting cultivation in West Africa savanna. In: mineral nutrients in tropical forest and savanna ecosystems (J. Proctor ed.), pp. 289-300. Oxford Blackwell Science Publications.

Lal, R. (1995). Trends in world agricultural land use: potentials and constraints. In: Soil management – experimental basis for sustainability and environmental quality (Lal, R., Stewart, B.A. eds.). CRC Press, Boca Raton, FL, pp. 521-536.

McGill, W.B., Cole, C.V. (1981). Comparative aspects of organic C, N, S and P cycling through organic matter during pedogenesis. Geoderma 26, pp. 267-286.

Moberg, J.P., Esu, I.E. (1991). Characteristics and composition of some savanna soils in Nigeria. Geoderma 48, pp. 113-129.

Ogunfowora, B. (1996). Input supply and distribution for crop production in Nigeria. Kenote address at the First ISNAR/NAERLS/FOA Joint Seminar, Ahmadu Bello University, Zaria, Nigeria.

Pennock, D.J., Kessel, van C. (1997). Clear-cut forest harvest on soil quality indicators in the mixedwood forests of Saskatchewan, Canada. Geoderma 81, pp. 13-32.

Peterman, R.M. (1990). Statistical power analysis can improve fisheries research and management. Canadian Journal of Fish and Aquatic Science 47, pp. 2-15.

Sposito, G. (1989). The chemistry of soils. Oxford University Press, New York.

Thomas, G.W. (1982). Exhangeable cations. In: Methods of soil analysis. Part 2. Chemical and microbiological properties (Page, A.L., Miller, R.H. and Keeney, D.R. eds.). American Society of Agronomy, Madison, WI. pp. 159-165.