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THE IMPACT OF LAND-COVER CHANGE ON SOIL PROPERTIES IN NORTHERN GHANA

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ABSTRACT

Effects of changes in land-cover on soil quality parameters in an area in northern Ghana were studied. Land-cover changes were derived from maps of the study area for 1984, 1992 and 1999. There were no significant differences between properties of soils under natural vegetation and soils put under cultivation from 1992, but permanently cultivated soils (1984–1999) showed significantly lower physical and chemical soil properties. Soils recently opened up since 1992 for cultivation in the last seven years (i.e. 1992–1999) were found to manifest significantly higher contents of organic C, N, Ca, Mg and ECEC than those under permanent cultivation, suggesting that continuous cropping is responsible for deterioration in soil quality. Minimum organic C contents necessary to meet critical levels of selected soil quality parameters were estimated. The organic C content of recently cultivated soils would need to be increased by about 7 $t\,ha^{-1}$ to replenish soil nutrient capital. This calls for a strategy to synchronize organic matter management with inorganic fertilizer application. Further research is also needed to develop farming systems that conserve organic matter and also improve the quality of organic matter in the study area.

KEY WORDS: dryland; land-cover change; nutrient replenishment; soil fertility

INTRODUCTION

Dryland inhabited by over 3 million people covers more than 40 per cent of Ghana's total land surface (Ghana Statistical Service, 2002). The predominant grasslands harbour few discontinuous strata of trees and shrubs. Intensive exploitation for crop and livestock production has led to profound degradation associated with hydrological and biogeochemical changes, and loss of habitats and biodiversity (Øygard *et al.*, 1999). Bush burning is an important source of carbon in the atmosphere (Stott, 1994), while loss of soil organic matter (SOM) destroys soil structure and accelerates desertification.

Research into the driving forces of such land-use/land-cover change focuses on remote sensing, agricultural census data, and biophysical and socioeconomic variables from thematic maps and socioeconomic surveys. Linear and logistic regression models are then used to relate land-cover to the presumed driving forces (Lambin *et al.*, 1999). Some studies (e.g. Priess *et al.*, 2001) have also investigated the impact of land-use change on the drivers. Focus is more and more on socioeconomic compared to biophysical drivers of land-use change. One reason is that nutrient depletion in agricultural production systems often occurs so creepingly that resource managers hardly contemplate initiating ameliorative measures. (Glantz, 1998). Furthermore, the role of biophysical drivers such as land quality in determining land-use change is often underestimated.

In dryland areas, plant nutrient supply is a major limiting factor for crop growth, and soil fertility depletion is the major biophysical cause of declining per capita food production (Øygard *et al.*, 1999). Traditional bush fallow is

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no longer adequate to restore soil fertility with ever-increasing population pressure on land resources. Continuous cropping with little or no inorganic fertilizer input leads to low nutrient balances (Smaling *et al*., 1997) and agricultural expansion into marginal lands exacerbates degradation of soil resources (Vlek, 1993; Greenland *et al*., 1997).

The negative consequences of nutrient depletion on food security and rural economy has led to numerous calls for more investment in nutrient capital (e.g. Izac, 1997). The specific objective of this study is to determine the effects of vegetation removal on soil properties, and the relative susceptibility of soil properties to changes in land-cover. Management implications of the observed changes are highlighted.

THE STUDY AREA

The study area of about 4800 km^2 (Figure 1) is located in the Guinea Savannah of the northern region of Ghana (8° 50′ and 10° N, and stretches between longitudes 0° 30′ to 1° 30′ W). Subsistence agriculture is the major means of livelihood in the area (Runge-Metzger and Diehl, 1993), with an average farm size of about 1 ha. Annual rainfall is about 1100 mm; the climate is tropical continental with a rainy season between May and September, and a prolonged dry season between October and March (Clottey and Kombiok, 2000). The slightly undulating land comprises sandstone and mudstone with a characteristic layer of iron-stone at shallow depths. Three soil groups can be distinguished: the reddish, well-drained upland sandy loams on the Upper Voltaian sandstones; the yellowish, imperfectly-drained sandy loams on slopes close to the valley bottoms; and the in-situ alluvial soils of the valley floors (Overseas Development Institute, 1999).

Remarkable demographic changes occurred in the last three decades. Population trends of three main localities are presented in Table I, showing that the population more than doubled between 1970 and 2000, with growth rate exceeding 2 per cent in the last 16 years (1984–2000). Increasing population pressure (Abudulai, 1996), low rainfall reliability (Andreini *et al*., 2000) and water insecurity (Asante *et al*., 2002) have reinforced migration as an alternative livelihood strategy for the rural population (Overseas Development Institute, 1999).

METHODS

Three land-cover change categories (trajectories) were defined within a geographical information system (GIS) using land-cover maps for 1984, 1992 and 1999 (Table II). The maps were prepared from Landsat Thematic Mapper (TM) images as part of the research efforts to study the effects of land-use on water resources in the Volta Basin of Ghana under the GLOWA project (http://www.glowa-volta.de). As one reviewer pointed out, the description of land-cover change categories in Table II only has meaning with respect to the timing of observation. For instance transition to cropland (Category 2) could have occurred at any time between 1984 and 1992.

One hundred and twenty (120) soil samples were collected within the three land-cover change categories along transects following the major road network. Sampling intervals varied from about 0·5 to 1·5 km along a transect. Samples collected from 0–20 cm depth were air-dried and passed through a 2 mm sieve, and subsequently analysed in the laboratory for pH (1 : 2·5 $CaCl_2$), organic C (Walkley-Black), available P (Bray-P), total N (Kjeldahl), exchangeable acidity (1*N* KCl), extractable bases (1*N* NH_4-acetate) and particle size (hydrometer method). Effective cation exchange capacity (ECEC) was calculated by summing up extractable cations and exchangeable acidity. Slope and elevation data of sampling points were derived from a digital elevation model constructed from 50 ft vertical interval contour lines of the study area.

RESULTS AND DISCUSSION

Summary of Dataset

The soils are generally silty to sandy in texture, probably due to the effects of wind deposition in the study area. The low contents of organic matter and clay resulting in poor soil structure may therefore explain why the soils are

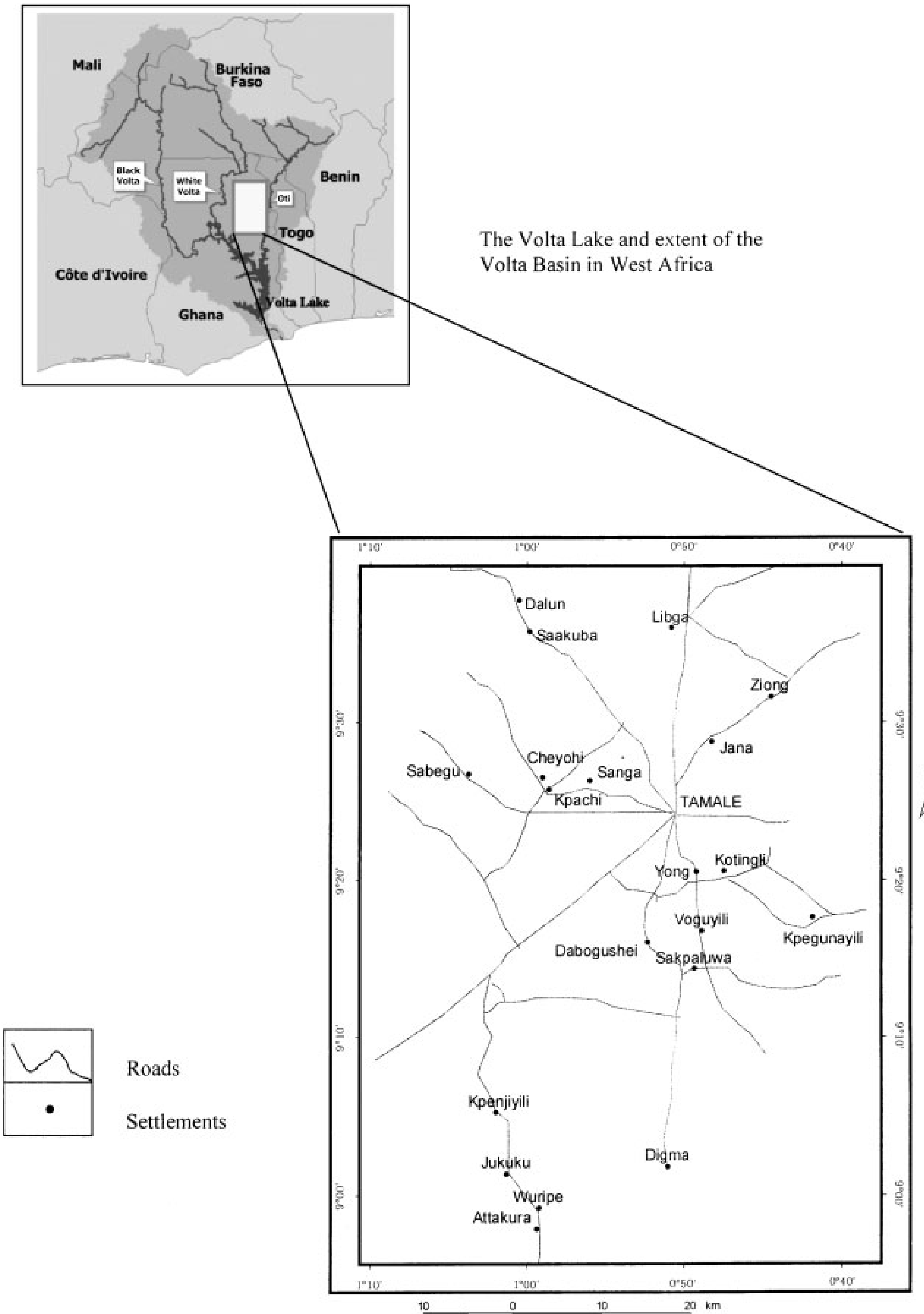

Figure 1. The study area.

Table I. Population trend for main localities in the study area

Locality	1970	Population in 1984	2000	% Increase 1970–1984	% Increase 1984–2000	%Growth rate 1984–2000
Savelugu	9895	16 965	24 937	71	47	2·4
Kumbungu	5157	7994	12 598	55	58	2·9
Tamale	83 653	15 952	2 02 317	63	49	2·5

Source: Ghana Statistical Service, 1989, 2002.

Table II. Land-cover change categories

Category	1984	Land-cover in 1992	1999	Description
1	Natural vegetation[a]	Natural vegetation	Natural vegetation	Non-cultivated land
2	Natural vegetation	Cultivated land	Cultivated land	Recent conversion to agriculture
3	Cultivated land	Cultivated land	Cultivated land	Permanent agriculture

[a]This refers to grassland and woodland.

very prone to erosion. Table III reveals that the soils are generally slightly acidic and highly deficient in C, N and P. The dominant exchangeable cation is Ca, with fairly high base saturation (60–99 per cent). The effective CEC is quite low (mean = 4·42 cmol kg^{-1}), a phenomenon related to the clay mineralogy (that is, kaolinitic 1 : 1 minerals) of the soils (Amatekpor, 1999). The coefficients of variation indicate that soil hue and elevation are the least variable physical properties (CV = 13 per cent), whereas the highest variation in physical properties was recorded

Table III. Statistics for the soils ($N = 120$)

	Mean	Minimum	Maximum	SD	CV (%)
pH	5·16	4·20	6·30	0·47	9
Organic carbon (%)	1·22	0·50	2·38	0·39	32
Total N (%)	0·06	0·00	0·28	0·04	65
Available P (ppm)	7·68	1·50	34·06	4·64	60
K (cmol kg^{-1})	0·22	0·04	1·36	0·22	99
Ca (cmol kg^{-1})	3·05	0·21	14·45	2·18	72
Mg (cmol kg^{-1})	1·03	0·07	3·87	0·66	64
EA (cmol kg^{-1})	0·11	0·01	0·71	0·12	112
ECEC (cmol kg^{-1})	4·42	0·84	17·02	2·74	19
Base saturation (%)	96·00	60·00	99·00	0·05	0
Hue[a]	3·89	2·00	5·00	0·50	13
Value	5·25	3·00	7·00	1·17	22
Chroma	3·41	1·00	6·00	1·24	36
Sand (%)	53·06	13·08	89·08	13·60	26
Silt (%)	39·81	8·84	83·84	12·50	31
Clay (%)	7·13	0·72	23·60	4·42	62
Slope (%)	7·01	2·00	20·00	4·66	66
Elevation (m)	163·70	119·00	234·00	21·19	13
Drainage[b]	1·62	1·00	3·00	0·68	42

[a]Soil colour is often described by the hue, value and chroma components of Munsell colour chart (Munsell Colour Company, 2000). Many soil-quality parameters can be inferred from soil colour. The hue notation is the dominant spectral colour and is indicated by characters R, Y, G, B, P representing Red, Yellow, Green, Blue and Purple respectively. Value represents the lightness of colour, and is represented numerically from 0 to 10. Chroma represents the degree of purity of the colour, and it takes value from 0 to 20. In this study, soil hues were coded as 2·5 YR = 1; 5 YR = 2; 7·5 YR = 3; 10 YR = 4 and 2·5 Y = 5.
[b]Drainage as an ordinal variable was coded as well-drained = 1; imperfectly drained = 2 and poorly drained = 3.
SD, standard deviation.

for slope (CV = 66 per cent). Coefficients of variation among soil chemical properties range from 0 per cent for base saturation to 112 per cent for exchangeable acidity.

Correlation Between Soil Properties

Table IV shows statistically significant correlations between many soil properties: pH with eleven other properties, and organic C is with ten properties. Nutrient availability is strongly pH-dependent and SOM is the storehouse of plant nutrients. Also ECEC is significantly correlated with ten other properties, notably more with organic C ($r = 0{\cdot}65$) than with clay ($r = 0{\cdot}35$). Decrease in organic matter will decrease ECEC, which may consequently lead to a reduction in the nutrient holding capacity of the soils. The significant correlations between organic C and clay ($r = 0{\cdot}23$) and between N and clay ($r = 0{\cdot}30$) suggest that the amounts of organic C and N in the soils are dependent on the amount of clay particles. Poorly drained soils are found in areas with low slope gradient. High chroma is associated with well-drained soils.

Effects of Land-cover Change on Soil Properties

Table V shows that permanently cultivated soils have the reddest hue (mean = 3·95), the highest value (lightness of colour) (mean = 5·59) and the highest chroma (strength of colour) (mean = 4·05). Among these soil-colour variables, chroma is significantly different between non-cultivated and permanently cultivated soils ($p < 0{\cdot}01$) (Table VI). They also significantly differ in terms of drainage. The fact that permanently cultivated soils are better drained than soils under natural vegetation reflects the preference of farmers for well-drained soils.

Permanently cultivated soils are on the lowest slopes (mean = 6·9 per cent), whereas soils recently converted to agriculture are on slightly higher slopes (mean = 7·0 per cent); the differences, however, are not significant. On average, land recently converted to agriculture is at the lowest elevation (mean = 158 m), followed by non-cultivated land (mean = 164 m) and permanently cultivated land (mean = 171 m). Elevation is significantly different ($p < 0{\cdot}05$) between recently cultivated and permanently cultivated soils. This can be explained by the settlement pattern and population dynamics (Abudulai, 1996). Population, and therefore agriculture, is largely concentrated around Tamale, which is at a higher elevation than the other localities.

Table IV. Intercorrelation of soil and land characteristics

	pH	Organic C	N	P	K	Ca	Mg	EA	Hue	Value	Chroma	Sand	Silt	Clay	ECEC	Base saturation	Slope	Elevation
Organic C	**																	
N	**	**																
P	**	**	**															
K	**	**	**	**														
Ca	**	**	**	**	**													
Mg	**	**	**	*	**	**												
EA	**	NS	NS	NS	NS	NS	NS											
Hue	**	NS	*	*	NS	*	NS	**										
Value	**	**	**	**	**	**	**	*	**									
Chroma	NS	**	**	NS	NS	**	**	NS	NS	**								
Sand	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS							
Silt	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**						
Clay	NS	*	**	NS	NS	**	**	NS	NS	*	NS	**	NS					
ECEC	**	**	**	**	**	**	**	NS	NS	**	**	NS	NS	**				
Base saturation	**	**	*	NS	*	**	**	**	**	**	NS	NS	NS	NS	**			
Slope	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS		
Elevation	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	**	NS	NS	NS	NS	NS	**	
Drainage	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	**	NS

*Significant at 0·05 level.
**Significant at 0·01 level.
NS, Not significant.

Table V. Statistics for soils of the land-cover change categories

	Non-cultivated land $n = 68$		Recent conversion to agriculture $n = 30$		Permanently cultivated $n = 22$	
	Mean	SD	Mean	SD	Mean	SD
Drainage	1·71	0·69	1·60	0·62	1·36	0·66
Slope (%)	6·99	4·56	7·13	4·42	6·91	5·45
Elevation (m)	163·97	19·96	157·73	22·06	171·18	22·30
Hue	3·87	0·54	3·90	0·31	3·95	0·58
Value	5·09	1·22	5·37	1·13	5·59	1·01
Chroma	3·15	1·18	3·53	1·22	4·05	1·25
Sand (%)	50·89	13·10	53·25	13·99	59·49	13·11
Silt (%)	41·29	12·20	39·89	13·35	35·13	11·63
Clay (%)	7·82	4·70	6·86	4·31	5·37	3·09
pH	5·19	0·51	5·21	0·38	5·01	0·47
Exchangeable acidity (cmol kg^{-1})	0·12	0·14	0·09	0·08	0·11	0·10
K (cmol kg^{-1})	0·22	0·18	0·25	0·29	0·19	0·24
Mg (cmol kg^{-1})	1·10	0·68	1·09	0·71	0·73	0·43
Ca (cmol kg^{-1})	3·23	2·28	3·33	2·43	2·14	1·11
ECEC (cmol kg^{-1})	4·67	2·79	4·76	3·08	3·17	1·57
Base saturation	96·00	6·00	98·00	1·00	96·00	4·00
N (%)	0·06	0·03	0·06	0·05	0·04	0·04
Available P (ppm)	8·42	5·52	7·18	3·45	6·06	1·89
Organic carbon (%)	1·27	0·39	1·28	0·44	1·00	0·23

Permanently cultivated soils have the highest sand content (mean = 59·5 per cent), while non-cultivated soils had the highest silt (mean = 41·3 per cent) and clay (mean = 7·8 per cent) contents. The differences between sand, silt and clay contents of non-cultivated and permanently cultivated soils are significant ($p < 0·05$).

Permanently cultivated soils had the lowest values of exchangeable bases K, Ca, Mg (Table V). Mean exchangeable K was not significantly different between the land-cover categories (Table VI), but there were significant differences in Mg, Ca and effective CEC between non-cultivated and permanently cultivated soils on the one hand, and soils recently converted to agriculture and permanently cultivated soils on the other. This supports the work of Kosmas *et al*. (2000) who noted a deterioration of soil fertility under continuous cropping as well as lower contents of exchangeable bases and CEC compared to soils under natural vegetation.

Permanently cultivated soils are slightly more acidic (mean pH = 5·0) than other land-cover categories (Table V), suggesting deterioration (decrease) in this soil quality parameter as cultivation persists. However, no significant differences were observed in pH and exchangeable acidity among the land-cover categories (Table VI).

The average total N of recently cultivated and non-cultivated soils were the same (mean = 0·06 per cent) and slightly higher than of soils under permanent cultivation (mean = 0·04 per cent); ($p < 0·05$). Organic C content for non-cultivated soils and soils recently converted to agriculture were also found to be similar and significantly higher than those of permanently cultivated soils ($p < 0·01$).

Properties that were significantly different between land-cover categories are presented in Table VII. There were no significant differences between properties of non-cultivated soils and soils put recently under cultivation after 1992. The soils recently opened up for cultivation were found to have significantly higher contents of organic C, N, Ca, Mg and ECEC than those under permanent cultivation. There were, however, no significant differences in physical properties suggesting that soil physical properties are more stable (that is, less prone to changes due to changes in land-cover) than chemical properties. Furthermore, permanently cultivated soils were found to exhibit a significantly lower status in physical and chemical soil properties compared to non-cultivated soils. This suggests that continuous cropping is primarily responsible for deterioration in soil quality in the study area.

Table VI. LSD test for parameters[a]

Physical properties				Chemical properties			
Soil properties	Land-cover change categories		M_d	Soil properties	Land-cover change categories		M_d
Hue	1	2	NS	pH	1	2	NS
	1	3	NS		1	3	NS
	2	3	NS		2	3	NS
Value	1	2	NS	Organic C	1	2	NS
	1	3	NS		1	3	**
	2	3	NS		2	3	**
Chroma	1	2	NS	N	1	2	NS
	1	3	**		1	3	*
	2	3	NS		2	3	*
Sand	1	2	NS	P	1	2	NS
	1	3	**		1	3	*
	2	3	NS		2	3	NS
Silt	1	2	NS	K	1	2	NS
	1	3	*		1	3	NS
	2	3	NS		2	3	NS
Clay	1	2	NS	Ca	1	2	NS
	1	3	*		1	3	*
	2	3	NS		2	3	*
Slope	1	2	NS	Mg	1	2	NS
	1	3	NS		1	3	*
	2	3	NS		2	3	*
Elevation	1	2	NS	EA	1	2	NS
	1	3	NS		1	3	NS
	2	3	*		2	3	NS
Drainage	1	2	NS	ECEC	1	2	NS
	1	3	*		1	3	*
	2	3	NS		2	3	*
				Base saturation	1	2	NS
					1	3	NS
					2	3	NS

[a]M_d refers to mean difference of parameters for the land-cover categories on the same row.
*Significant at 0·05 level.
**Significant at 0·01 level.
NS, Not significant.

Table VII. Properties that were statistically different between land-cover change categories

Non-cultivated (1) versus permanently cultivated (3)	Recently cultivated (2) versus Permanently cultivated (3)
Drainage	Organic C
Sand	N
Silt	Ca
Clay	Mg
Chroma	ECEC
Organic C	Elevation
N	
P	
Ca	
Mg	
ECEC	

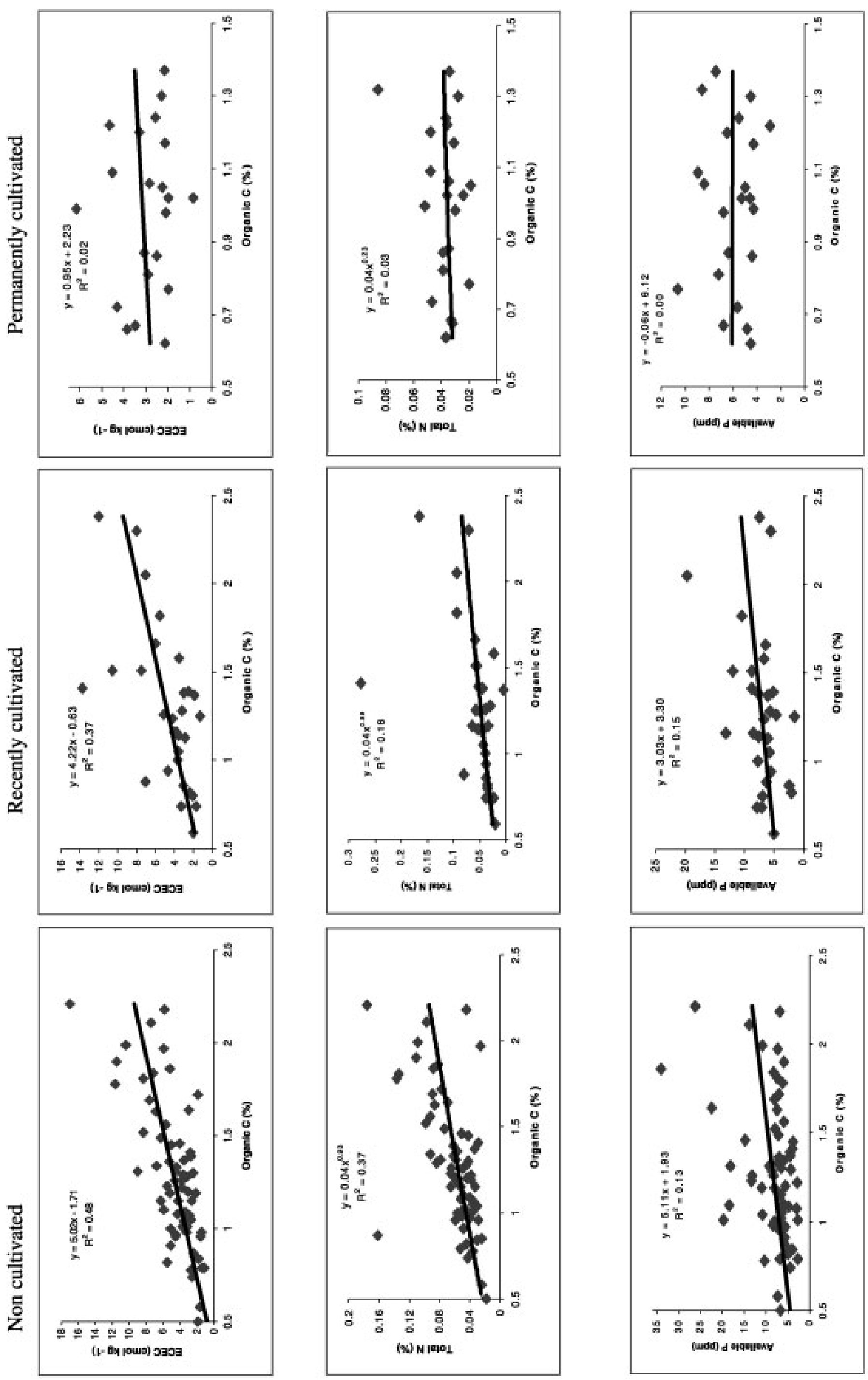

Figure 2. Functional relationship between organic C and selected soil properties.

Table VIII. Estimated minimum organic C content for selected soil quality parameters

Soil property	Critical level	Non-cultivated soils $n = 68$ Minimum organic C level (%)	Non-cultivated soils Deficit organic C C (%)[a]	Non-cultivated soils Deficit organic C ($t\,ha^{-1}$)[b]	Recently Cultivated soils $n = 30$ Minimum organic C level (%)	Recently Cultivated soils Deficit organic C C (%)	Recently Cultivated soils Deficit organic C ($t\,ha^{-1}$)**
ECEC	$8\,cmol\,kg^{-1}$	1·93	0·66	1·79	2·04	0·76	2·13
Total N	0·1%	2·37	1·10	3·04	2·88	1·60	4·48
Available P	15 ppm	2·56	1·29	3·61	3·86	2·58	7·22

[a]Obtained by subtracting mean organic C for the land-cover category from the estimated crucial organic C level.
[b]Assumes bulk density of sampled layer is $1{\cdot}40\,g\,cm^{-3}$.

Functional Relationships Between Soil Characteristics

The correlation of organic C with many soil properties, its high variance related with land-cover change, as well as its documented role in agricultural sustainability make organic-matter management important for fertility management of the soils. A vital question, however, is whether organic matter management alone could replenish the fertility status of the soil to guarantee food security.

Figure 2 shows that the relationships between organic C and the soil quality indices ECEC, P and N are weakest for permanently cultivated soils. This suggests that correlation between organic C and these parameters decreases with cultivation. This observation reflects the awful consequence of nutrient mining of the soils.

Table VIII indicates that the minimum organic C levels to achieve critical levels for the parameters ECEC, N and P are higher for recently cultivated land. We did not carry out any calculations for the permanently cultivated land because a relationship between the parameters and organic C is virtually non-existent. For recently cultivated and non-cultivated soils, the minimum organic C requirements for the parameters are in the order P > N > ECEC. Table VIII further indicates the deficit in organic C required to meet the critical level for each parameter. However, accumulation of organic matter in a savannah environment is very slow and it is difficult to make up for such deficits using organic inputs alone. It needs about $7\,t\,ha^{-1}$ to replenish recently cultivated soils (Table VIII). Problems associated with addition of large amounts of organic manure have been discussed by Giller *et al*. (1997) and Palm *et al*. (1997). These include low quality of organic inputs generated by farmers, high labour and transportation costs and losses through leaching and denitrification. The low P content of organic inputs also makes them a poor supplier of P.

The overall soil management implication is that a considerable investment in inorganic fertilizers will be required (Vlek *et al*., 1997), as removal of P from the soil is mainly by crop harvest and P is not replenished by nutrient recycling. Nitrogen on the contrary, is at least partially replenished by nitrogen fixation through *Azotobacter* and leguminous plants.

SUMMARY AND CONCLUSION

This study suggests that continuous cultivation depletes soil nutrients. Even though there is correlation between organic C and many soil properties, the correlation decreases as cultivation persists. With the loss of SOM, materials that contribute little to soil fertility are left. There is a need to combine organic materials and inorganic fertilizers to replenish soil nutrients. Furthermore, there is a need for research on the quality of organic matter in drylands. Such research should improve the understanding of determinants of SOM stability, mineralization and immobilization of nutrients from SOM, and also N and P transformation processes in such environments. Farming systems that conserve SOM and minimize cultivation also need to be developed.

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