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Carbon and Nitrogen Stocks of the Central Clay Plane: Irrigated versus Rain-fed Vertisols

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ABSTRACT

Mitigation of atmospheric CO_2 concentration and ensuring national food security could be achieved by increasing carbon sequestration in the soil. We estimated soil organic C and N sequestered in the long- (79 years), medium- (46 years) and short-term (22 years) crop rotation systems of cotton (*Gossypium hirsutum*), sorghum (*Sorghum bicolor*), groundnut (*Arachis hypogaea*), wheat (*Triticum aestivum*) and fallow in Vertisols, both irrigated and rain-fed, of the semi-arid tropics of Sudan. Total C pool, comprising soil organic and inorganic C for the entire profile (0 - 0.90 m) of irrigated Vertisols was estimated to be 142, 174 and 99 t ha^{-1} C for the short-, medium- and long- term cultivation, respectively. Under irrigated soils, organic C made up 31 to 71% of the total C stored in the profile compared to 63 to 73% under rain-fed Vertisols. It was estimated that about 25% was lost from total profile (0 - 0.9 m) C as CO_2 after about 79 years of cultivation (0.414 t C ha^{-1} yr^{-1}) of the Gezira cotton scheme. Similarly, loss from organic C was estimated at 29% with a rate of 0.208 t C ha^{-1} yr^{-1}. Total profile (0 - 0.9 m) N under short- and medium-term cultivation (6.74 – 7.79 t ha^{-1}) was significantly higher than that under long-term cultivation (5.05 t N ha^{-1}). However, cropping system had no significant effect on total N (an average of 8.0 t ha-1) under rain-fed Vertisols. About 65 to 68% of total profile N was found below the plough layer (0 – 0.3 m). Since Vertisols are heavy clay soils, reducing tillage operations, an alternative management practice (for example, using cover crops during fallow periods and retaining crop residues in situ) would help in reducing C loss in one of the largest cotton schemes in Africa.

Keywords: Carbon, nitrogen, sequestration, semi-arid, Sudan, Vertisols

INTRODUCTION

The agricultural sector in Sudan produces about 90% of the national food requirement and it comprises different sub-sectors: irrigated mechanised and traditional rain-fed agriculture, livestock and forestry (Abdel Nour 1999). More than 100 million ha of the worldwide Vertisols (320 million ha) occur in Africa with about 70 million ha in Sudan (Ayoub 2001; Dalal 2003). Blokhuis (1993) identified two clay plains in Sudan, the Central Clay Plain, also known as Northern

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Clay Plain (70% of total Sudan Vertisols) with dark, cracking clays, not subject to prolonged annual flooding, and a southern plain (Southern Clay Plain), where clays are predominant, but far less so than in the northern part, and where all land is subject to long periods of annual flooding. The Gezira (Gezira in Arabic means: island), Managil Extension and Rahad (areas of the present study) are among the geographic regions of the Central Clay Plain. The Gezira Scheme represents half of the total irrigated land of the country and contributes 46, 23 and 12% of the total production of wheat, groundnuts and dura, respectively (Ahmed 2004).

The soil environment in the irrigated Vertisols favours high soil organic matter mineralisation. This was earlier attributed to the frequent wetting/drying cycles that results in warm and wet conditions (Hulugalle 2000). Soil was reported to be the largest terrestrial pool of C and it stores about 2157 - 2296 Pg of C, about 1462 – 1548 Pg of organic C and about 133 - 140 Pg of soil N in the upper 1 m (Batjes 1996). Most of the total soil C in soils of arid and semi-arid regions occurs as secondary carbonates (Knowles and Singh 2003). Globally, inorganic C constitutes an average of 32% of the total soil C. Size and dynamics of the C and N pools in the world's soils are poorly understood (Legros *et al*. 1994). In the tropics, soil C and total N to 1 m depth account for about 26 and 32% of the world total organic C and total N, respectively (Batjes 1996).

Studies on TN, C and C/N ratio of the Gezira scheme were conducted during the years of 1946 to 1952 (Jones 1957; 1958a; 1958b). Although there were useful data on these studies, C and N sequestration to lower depths were not included. In addition, most published data in the area of study concentrated on either impact of tillage on water conservation, crop yield, soil physical properties (Dawelbeit and Babiker 1997; Salih *et al*. 1998; El-Awad 2000) or evaluation of topsoil (0 - 0.30 m) pH, electrical conductivity or sodium adsorption ratio (Buraymah and Webster 1989). There is no detailed study of the C and N pools in the irrigated Gezira scheme. The aim of this study was to estimate soil C and N pools in Vertisols from (1) long (79 years), medium (46 years) and short - term (22 years) cropping systems of irrigated Vertisols with various rotations and (2) in the soil profiles from rain-fed Vertisols.

MATERIALS AND METHODS

Study Sites

Sudan has several agro-ecological zones with varying climatic conditions. The (a) arid zone covers 29% of the total area of the country with no rainfall and hence no vegetation cover; (b) semi-arid zone comprises 20% of the total country area with rainfall ranging from 50 to 300 mm yr^{-1}; (c) Savannah, 30.8% of the total country and rainfall of 200 to 1500 mm yr^{-1}; and (d) montane with rainfall of more than 1500 mm yr^{-1}. Three study sites (*Fig. 1*) from the irrigated Vertisols of the semi-arid region of Sudan with different durations of cropping history were sampled to evaluate soil C and N storage. Location, mean annual rainfall and temperature are shown in Table 1 while soil physical and chemical properties of the irrigated and rain-fed Vertisols are given in Tables 2 and 3, respectively. The sites selected are the Gezira (G), Managil (M) and Rahad (H) schemes representing the irrigated schemes under long, medium and short-term cropping durations,

TABLE 1
Mean annual rainfall (*MAR)*, minimum annual temperature (*Min. AT*), maximum annual temperature (*Max.AT*) at the study sites in Sudan

Study Site	Longitude	Latitude	Elevation m absl	MAR mm yr^{-1}	Min.AT	Max.AT
					°C	
G	33° 30' E	14° 24' N	390	200 - 450	13	40
M	32° 49' E	14° 14' N	390	200 - 450	13	40
H	34° 22' E	13° 43' N	600	350 - 650	10	35

G: Gezira M: Managil H: Rahad

respectively. Rain-fed Vertisols are located in eastern Rahad. According to Soil Survey Staff (1996), the soils of all sites were classified as fine montmorillonitic, isohyperthermic, enticchromustert. The cropping system of the rain-fed Vertisols are continuous sorghum (*Sorghum bicolr*) (CS) and a sorghum-sesame (*Sesamum indicum*) (S-S) rotation (>30 years). Crop rotation in the irrigated schemes varies in accordance with the prevailing agricultural environment that was established with the different stages of development in the schemes. Historical background of the cropping sequences and technical packages of the irrigated Vertisols are shown in Table 4 and Table 5, respectively. The main crops include cotton (*Gossypium barbadense* L.) sorghum (*Sorghum bicolor* L.), groundnut (*Arachis hypogaea* L.) and wheat (*Triticum aestivum* L.). Inside the irrigated schemes there are permanent fallow plots (PF) kept without cultivation since 1937. This grassland plots (C4 grasses), are neither fertilised nor grazed and were sampled to represent the control of the irrigated Vertisols. For the control of the rain-fed Vertisols, samples were collected from a natural forest (NF) area occupied mainly by Accacia spp.

Sampling and Analysis

Soil samples were taken in June 2004 before the onset of the rainy season. Within each site, the area selected for sampling was 90 ha. In each site, samples were taken from three replicate profiles (one profile/30 ha) and, therefore, the total number of profiles investigated in this study was 21. Bulk samples from each depth (0 – 0.1, 0.1 – 0.2, 0.2 – 0.3, 0.3 – 0.5, 0.5 – 0.7 and 0.70 – 0.9 m) were thoroughly mixed in the field and a representative sample was placed into a cotton bag and transferred to the laboratory. A total of 126 soil samples (that is, for the irrigated Vertisols: 4 sites x 6 depths x 3 profiles = 72 samples; for rain-fed: 3 sites x 6 depths x 3 profiles= 54 samples) were taken for determination of organic C, inorganic C, total C (TC) and total N (TN). Samples were air-dried and sieved subsequently through a 2-mm sieve to remove fine roots and gravel. Both total soils C (finely ground, 140-mesh) (TC) and N (TN) were determined using a dry combustion analyser (Vario EL III, CHNOS, Elementer, Germany). Soil inorganic C (carbonate-C) was determined from the ≤ 2 mm samples by the pressure transducer method adapted from Loeppert and Suarez (1996), assuming 12% C in $CaCO_3$. Bulk density was determined using the core method developed by Blake and Hartge (1986). Organic

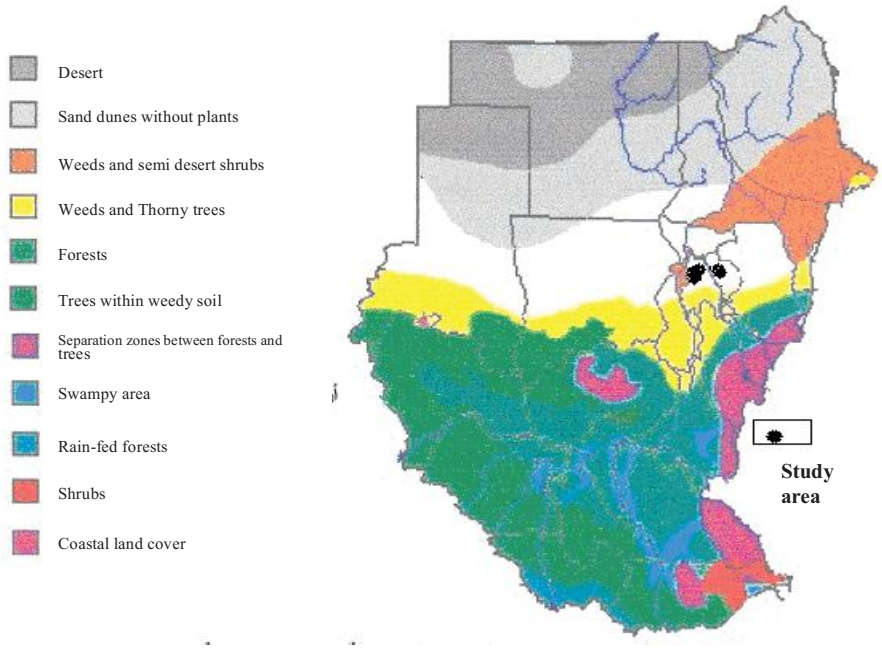

Fig. 1: Location of the study site (Adapted from Wickens 1991).

C (t ha^{-1}) was determined by subtracting inorganic C from values of TC followed by summing up all depth intervals (Lal 1997). Contribution of soil organic C in each depth to total soil C was calculated as follows:
Contribution of soil organic C to total C (%) = content of organic C in each depth/ total profile C

Statistical analysis was carried out to determine differences in C and N stocks in the irrigated and rain-fed Vertisols separately. Data were arranged in a randomised block design for ANOVA and means were separated with the least signfifcant difference (LSD) at a probability of ≤ 0.05 using SAS (1985).

RESULTS AND DISCUSSION

Total and Organic C

Under irrigated Vertisols, cultivation (compared to permanent non-irrigated fallow) significantly (P ≤ 0.001) increased OC of the top 0.0 - 0.1 and 0.1 - 0.2 m depths from 2.63 to 12.20 t ha^{-1} and 2.04 to 10.04 t C ha^{-1}, respectively (Table 6). Under similar climatic conditions of Sudan (189 mm – 642 mm yr^{-1}), Hiraika (1991) found that organic C increased with cultivation period (13 years) by about 3 to 14% (0.0 - 0.3 m) and this was attributed to the input of plant residues during harvest. However, within the cultivated sites, significant differences were found between sites when the period of cultivation was increased from 22 years (Rahad) to 46 years (Managil) and 79 years (Gezira). Accordingly, OC in the 0.0 - 0.1, 0.1 - 0.2, 0.2 - 0.3, 0.3 - 0.5, 0.5 - 0.0 and 0.7 - 0.9 m soil profile in Rahad site (12.2,

TABLE 2
Physical and chemical characteristics of the different sites within the study area
(Irrigated Vertisols)

Site	pH	%OC	%TN	%$CaCo_3$	Bd kg dm^3	Sand	Silt	Clay
						%		
				0.0 - 0.1 m				
G	8.1	0.351	0.033	3.70	1.6	13.8	16.7	69.5
M	8.0	0.537	0.048	5.79	1.6	21.4	15.8	62.8
H	8.0	0.718	0.059	1.79	1.7	05.5	15.0	79.5
PF	8.1	0.146	0.036	3.53	1.8	13.1	15.7	71.2
				0.1 - 0.2 m				
G	8.2	0.269	0.031	2.59	1.7	09.4	16.7	73.9
M	8.2	0.441	0.043	5.71	1.8	17.2	18.3	64.5
H	7.9	0.671	0.051	2.13	1.5	06.7	13.3	80.0
PF	8.3	0.120	0.036	4.54	1.7	09.6	16.7	73.7
				0.2 - 0.3 m				
G	8.1	0.111	0.032	3.69	1.7	12.1	15.0	72.9
M	8.0	0.424	0.046	6.75	1.8	13.0	20.8	66.2
H	8.0	0.582	0.051	2.94	1.7	05.6	14.2	80.2
PF	8.3	0.983	0.037	3.67	1.7	16.0	16.2	67.8
				0.3 - 0.5 m				
G	8.1	0.232	0.031	2.86	1.8	09.6	16.7	73.7
M	8.2	0.402	0.041	6.39	1.8	18.0	15.8	66.2
H	8.2	0.645	0.050	2.27	1.8	06.4	11.7	81.9
PF	8.3	0.195	0.033	3.86	1.8	14.8	15.7	69.5
				0.5 - 0.7 m				
M	8.2	0.418	0.043	6.84	1.7	16.3	15.0	68.7
H	8.2	0.624	0.051	2.22	1.8	05.3	13.3	81.4
PF	8.1	0.420	0.034	4.57	1.8	06.4	15.7	77.9
				0.7 - 0.9 m				
G	7.9	0.347	0.032	2.99	1.9	10.0	17.1	72.9
M	8.3	0.539	0.039	6.33	1.8	12.2	15.8	72.0
H	8.1	0.633	0.043	1.92	1.9	05.4	12.1	82.5
PF	7.9	0.412	0.035	3.29	1.7	05.4	16.7	77.9

G: Gezira M: Managil H: Rahad PF: Permanent fallow Bd: Bulk density

TABLE 3
Physical and chemical characteristics of the different sites within the study area
(Rain-fed Vertisols)

Site	pH	%OC	%TN	%$CaCo_3$	Bd kg dm^{-3}	Sand	Silt	Clay
						%		
				0.0 - 0.1 m				
NF	7.9	0.649	0.064	3.13	1.6	13.0	15.8	71.2
S-S	7.5	0.774	0.067	1.95	1.6	14.0	16.5	69.5
CS	7.9	0.839	0.062	1.99	1.5	21.3	15.8	62.9
				0.1 - 0.2 m				
NF	8.1	0.608	0.066	3.07	1.6	9.6	16.7	73.7
S-S	7.5	0.859	0.063	2.01	1.6	9.4	16.7	73.9
CS	8.0	0.716	0.061	2.39	1.6	16.9	18.6	64.5
				0.2 - 0.3 m				
NF	8.2	1.033	0.061	3.09	1.5	13.0	19.2	67.8
S-S	7.9	0.792	0.058	3.09	1.5	12.1	15.0	72.9
CS	7.9	0.806	0.059	2.56	1.4	13.0	20.8	66.2
				0.3 - 0.5 m				
NF	7.9	0.757	0.059	2.93	1.6	11.4	15.8	72.8
S-S	7.8	0.621	0.061	2.65	1.6	9.6	16.7	73.7
CS	8.1	0.820	0.059	2.18	1.6	18.0	15.8	66.2
				0.5 - 0.7 m				
NF	8.0	0.547	0.053	3.58	1.5	6.3	15.8	77.9
S-S	7.8	0.769	0.052	2.82	1.5	3.1	22.4	74.5
CS	8.1	0.759	0.054	2.61	1.6	16.3	15.0	68.7
				0.7 - 0.9 m				
NF	8.1	0.511	0.053	3.19	1.7	5.0	17.1	77.9
S-S	7.9	0.671	0.051	2.47	1.7	9.6	17.5	72.9
CS	8.0	0.671	0.052	2.41	1.6	12.1	15.9	72.0

NF: Natural Forest S-S: Sorghum Sesame CS: Continuous Sorghum Bd: Bulk density

TABLE 4
Historical background of the rotations in the irrigated Vertisols of Gezira, Managil and Rahad Schemes, Sudan

Gezira		Managil		Rahad	
Period	Crop sequence	Period	Crop sequence	Period	Crop sequence
1925-1931	C-S/L-Fa	1958-1960	C-Fa-C-Gn/S/L-S-Fa	1982-1990	C-Gn
1932-1933	C-Fa-Fa	1961-1975	C-W-Gn/S	1990-Present	C-Gn-S/W
1934-1960	C-Fa-Fa-C-Fa-S-L/Fa-Fa	1976-1988	C-W-Gn/S/Veg-Fa		
1961-1974	C-W-Fa-C-Gn/L-S-P-Fa-Fa	1989-1990	C-W-Gn/S/Veg-Fod-Fa		
1975-1986	C-W-Gn/S/Veg-Fa	1991-Present	C-S-Gn-W-Fa		
1987-1990	C-W-Gn/Veg-Fod-Fa				
1991-Present	C-S-Gn-W-Fa				

Crops:
C: Cotton, S:Sorghum, L:Legume, Fa: Fallow, W: Wheat, Gn: Groundnut, P: Philipisara, Veg: Vegtable, Fod: Fodder crop, /: and or

10.1, 9.9, 23.2, 22.5 and 22.8 t ha-1, respectively) was significantly higher than that in Gezira site (5.6, 4.6, 1.9, 8.4, 7.5 and 13.2 t C ha^{-1}) and Managil site (8.6, 7.9, 8.0, 8.89, 10.991 and 9.46 t C ha^{-1}). Total organic C sequestered in the top 0.0 - 0.9 m depth (bulk density varies from 1.5 to 1.9 kg dm^{-3}) in the permanent fallow, Gezira (long-term), Rahad (short-term) and Managil (medium-term) sites were 57.5, 41.1, 100.6 and 54 t C ha-1, respectively. It was found that (across all sites) the topsoil (0.0 - 0.3 m) contributed about 29 to 38% (average 33%) of the total OC in the profile. Similarly, OC contributed about 45, 41, 71 and 31% of the total C stored in the profile of PF, G, H and M respectively (*Fig. 2*). Total 0.0 - 0.9 m C stored in M profile (174 t C ha^{-1}) was significantly ($P \leq 0.01$) higher than that sequestered in the PF (132 t C ha^{-1}), G (99 t C ha^{-1}) and H (142 t C ha^{-1}). The content of $CaCO_3$ in PF, G, H and M was found to vary from 3.2 to 4.5%, 2.5 to 3.7%, 1.8 to 2.9% and 5.8 to 6.7%, respectively (Table 3). As mentioned earlier, the PF plot was taken as a control plot and is just beside the G plots; keeping this in mind, total OC in the profile (0.0 - 0.9 m) of G (41.1 t C ha-1) was less than that under PF plots (57.5 t C ha-1) by about 32%. The increase in OC in the top 0.2 m depth could be due to more inputs of crop residues (below and above ground). Moreover, PF did not receive any management practice (e.g. irrigation or fertilisation). Organic C content is relatively higher in deeper layers (> 0.3 m) which reflects the inversion characteristics of the Vertisols (Mendham *et al*. 2003). This is consistent with results of Knowles and Singh (2003) who studied C sequestration in the Vertisols of New South Wales. Decrease in OC with inappropriate cultivation is well documented (Bronson *et al*. 2004; Brye *et al*. 2004). With the exception of H, inorganic C made up about 55 to 62% of total C (*Fig*. 4). Knowles and Singh (2003) reported values higher than global average and they attributed it to the formation of carbonates (Arkley 1963). Carbonate concentration in the soil of this study site varied from 3.5 to 7.4% which could be due to parent material.

Under rain-fed Vertisols, generally OC stored in the profile (0.0 - 0.9 m) of all management practices were similar (bulk density ranged from 1.5 to 1.7 kg dm^{-3}) and ranged from 94 (in the natural forest) to 107 t C ha^{-1} (in the continuous sorghum, CS) (Table 7). Total OC in the top 0.0 - 0.3 m depth was also not significantly different between cropping systems under rain-fed Vertisols (36 – 38 t C ha^{-1}). Only 34 to 38% of total profile OC was found in the top 0.0 - 0.3 m depth. Total C (0.0 - 0.9 m) values recorded under S-S and CS of rain-fed Vertisols are quite similar (average 148 t C ha^{-1}). However, the proportion of total profile C contributed by OC was found to be more than 60% (64 - 73%) (*Fig. 3*) whereas the proportion of total C contributed by inorganic C was found to be higher in the NF (36%) compared to S-S (29%) and CS (27%) (*Fig.5*). Rain-fed Vertisols retained higher amounts of OC (104 – 109 t C ha^{-1}) compared to long-term irrigated Vertisols (42 – 72 t C ha^{-1}). This is probably due to less intense soil manipulation in rain-fed areas, where wide level disc is the only tillage operation used. Moreover, farmers practise a traditional system of rain water catchment and that can improve water conservation. An improved system of water catchment management in combination with appropriate practices can improve soil quality (Wani *et al*. 2003). Total C pool for the entire profile (0.0 - 0.9 m) in sampled

areas (90 ha) was estimated at approximately 8909, 12758 and 19691 t C stored in Gezira, Rahad and Managil, respectively; the corresponding amount of OC was 3695, 9055 and 4844, respectively. The permanent fallow (PF) plots are just beside the Gezira (G) scheme and therefore, typically represent the scheme. If the area sampled had been left fallow since the start in 1925, total C sequestered in the 0 - 90 cm depth would have been about 11851 t C. Accordingly, about 2943 t C (25%) was lost as CO_2 since the start of cultivation (that is, 0.414 t C ha^{-1}yr-1). Similarly, the content of organic C that would have been sequestered is about 5177 t O.C., of which 1482 (29%) and 934 t O.C. (7%) were lost as CO_2 in the long and medium-term cultivation respectively (0.208 and 0.081 t C/$ha^{-1}yr^{-1}$). Therefore, to maintain organic C equilibrium in the soil profile, 81 to 208 kg C should come from crop residues, roots or manure. Kundu *et al*. (2001) reported that about 887 kg C $ha^{-1}yr^{-1}$ is required by Indian Vertisol to maintain C equilibrium. In Pacific North-West soils, C inputs ranging from 200 to 2000 kg C ha^{-1} yr^{-1} were required to maintain soil organic matter content (Rasmussen and Albrecht 1998). Relatively low values in these soils could be attributed to high clay content that slows decomposition of added C by enhancing physical protection (Hassink 1994).

Total N

Total N stored in the profile followed almost a similar trend to OC. Long-term cultivation (G) decreased TN in the top 0.3 m depth from 1.87 t/ha to 1.61 t ha^{-1} (that is, 14% reduction) (Table 6) and also TN profile (0.0 – 0.9 m) storage from 5.46 t ha^{-1} to 5.05 t ha^{-1} (8% reduction). Also, TN in the profile (0.0 - 0.9 m) of the short (7.79 t ha^{-1}) and medium-term cultivation (6.74 t ha^{-1}) of the Vertisols were statistically higher ($P \leq 0.01$) than that in long-term cultivation (5.05 t ha^{-1}). Under all cultivation systems, more than 60% (64 - 68%) of the TN stored in the profile (0.0 - 0.9 m) was found below the plough layer (0.0 - 0.3 m). These values (5.1 – 8.2 t N/ha^{-1}) are lower than estimates of world Vertisols-N pool where values recorded are 5, 7.5 and 12.3 t N ha^{-1} for the 0.0 - 0.3, 0.0 - 0.5 and 0.0 - 1 m depth, respectively (Batjes 1996). These studies showed high variability (C.V. ranged between 42 and 58%). Under rain-fed areas, TN stored in the various layers is also generally quite similar with an average total profile content of 8.0 t ha^{-1}

In both irrigated and rain-fed cultivated Vertisols, the C/N ratio (ranged from 4 to 14) of the soil remained almost the same throughout the profile which is consistent with values (average of 13 for the 0.0 - 0.3, 0.0 - 0.5 and 0.0 - 1 m depth) obtained earlier by Batjes (1996). This reflects the intense mixing of the deep cracking and swelling clay soils.

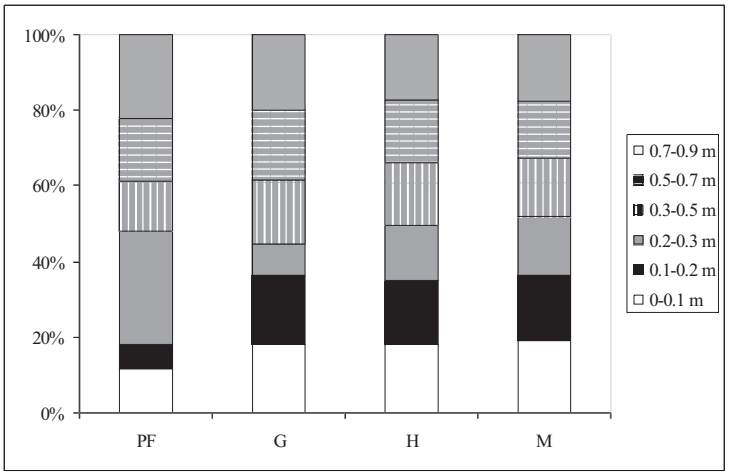

Fig. 2: Contribution of soil organic carbon in the different to total soil carbon in the profile (%) in the permanent fallow (PF), Gezira rotation (G), Rahad rotation (H) and Managil rotation in the irrigated Vertisols

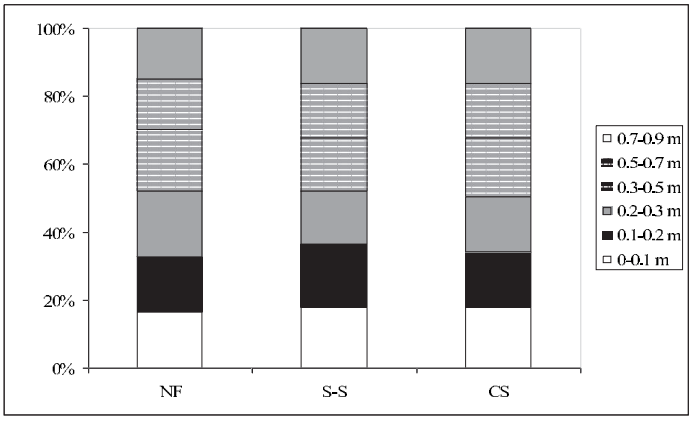

Fig. 3: Contribution of soil organic carbon in the different depths to total soil carbon in the profile (%) in the natural forest (NF), sesame-sorghum rotation (S-S) and continuous sorghum (CS) in the rain-fed Vertisols

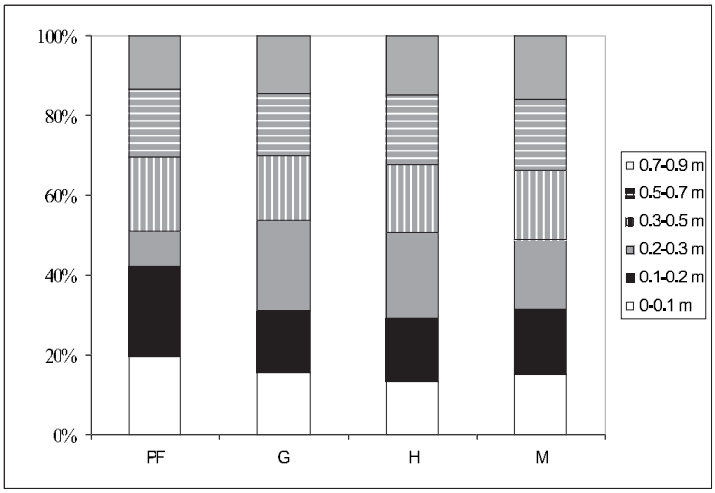

Fig. 4: Contribution of soil inorganic carbon in the different soil depths to total soil carbon in the profile (%) in the permanent fallow (PF), Gezira rotation (G), Rahad rotation (H) and Managil rotation in the irrigated Vertisols

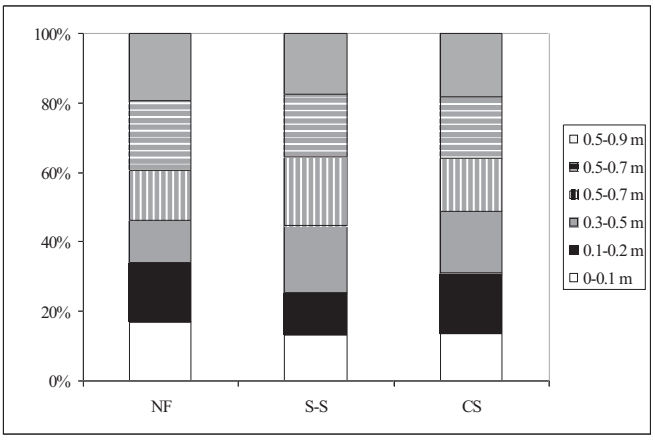

Fig. 5: Contribution of soil inorganic carbon in the different soil depths to total soil carbon in the profile (%) in the natural forest (NF) sesame-sorghum rotation (S-S) and continuous sorghum (CS) in the rain-fed Vertisols

TABLE 5
Crop tillage and fertilisation under irrigated Vertisols

Crop	Tillage and fertilisation
C	Disc ploughing (0.18 - 0.20 m), harrowing (0.10 - 0.15 m), ridging, green ridging, 120 kg N ha^{-1}
W	Disc harrowing (0.06 - 0.07 m), leveling, 80 kg N ha^{-1}, 90 kg TSP ha^{-1}
S	Disc harrowing (0.15 - 0.17 m), ridging, 80 kg N ha^{-1}
Gn	Disc harrowing (0.15 m), ridging, green ridging

C: Cotton S: Sorghum W: Wheat Gn: Groundnut

TABLE 6
Total C, organic C, inorganic C and total pools for six depths of the irrigated Vertisols [(means (standard deviations)] and reference fallow plot (PF).

Cultivation System	Carbon t ha^{-1}			Total N t ha^{-1}
	Organic C	Inorganic C	Total C	
		0.0 - 0.1 m		
G	5.62 (0.13) ^{c}	7.10 (0.08) ^{b}	12.72 (0.70) ^{bc}	0.53 (0.002) ^{c}
M	8.59 (0.26) ^{b}	11.14 (0.22) ^{a}	19.73 (0.32) ^{a}	0.77 (0.005) ^{b}
H	12.20 (0.09) ^{a}	3.66 (0.15) ^{c}	15.86 (0.12) ^{b}	0.99 (0.014) ^{a}
PF	2.63 (0.04) ^{d}	7.61 (0.11) ^{b}	10.24 (0.10) ^{c}	0.64 (0.005) ^{c}
		0.1 - 0.2 m		
G	4.56 (0.24) ^{c}	5.29 (0.09) ^{b}	9.84 (0.17) ^{b}	0.53 (0.003) ^{c}
M	7.94 (0.09) ^{b}	12.33 (0.05) ^{a}	20.27 (0.17) ^{a}	0.78 (0.004) ^{a}
H	10.07 (0.12) ^{a}	3.83 (0.19) ^{b}	13.89 (0.13) ^{a}	0.77 (0.006) ^{a}
PF	2.04 (0.27) ^{d}	9.27 (0.10) ^{a}	11.31 (0.36) ^{b}	0.61 (0.007) ^{c}
		0.2 - 0.3 m		
G	1.89 (0.12) ^{b}	7.53 (0.09) ^{b}	9.42 (0.36) ^{c}	0.55 (0.009) ^{c}
M	7.96 (0.09) ^{b}	14.24 (0.14) ^{a}	22.19 (0.21) ^{ab}	0.83 (0.014) ^{ab}
H	9.89 (0.15) ^{b}	5.99 (0.29) ^{b}	15.88 (0.14) ^{b}	0.86 (0.003) ^{a}
PF	16.71 (0.79) ^{a}	7.48 (0.22) ^{b}	24.19 (0.56) ^{a}	0.62 (0.005) ^{bc}
		0.3 - 0.5 m		
G	8.35 (0.58) ^{bc}	12.35 (0.61) ^{b}	20.70 (0.16) ^{c}	1.11 (0.007) ^{c}
M	8.89 (0.04) ^{b}	27.61 (0.47) ^{a}	36.50 (0.42) ^{a}	1.49 (0.022) ^{b}
H	23.22 (0.22) ^{a}	9.79 (0.47) ^{b}	33.01 (0.36) ^{b}	1.79 (0.014) ^{a}
PF	7.02 (0.22) ^{c}	16.67 (0.39) ^{ab}	23.69 (0.19) ^{c}	1.18 (0.007) ^{c}
		0.5 - 0.7 m		
G	7.46 (0.47) ^{a}	11.98 (0.54) ^{c}	19.44 (0.83) ^{b}	1.11 (0.007) ^{c}
M	10.99 (0.17) ^{a}	27.85 (0.27) ^{a}	38.84 (0.44) ^{a}	1.46 (0.026) ^{b}
H	22.46 (0.18) ^{a}	9.58 (0.39) ^{c}	32.04 (0.36) ^{ab}	1.83 (0.011) ^{a}
PF	15.12 (0.16) ^{a}	19.73 (0.18) ^{b}	34.85 (0.26) ^{a}	1.22 (0.011) ^{c}
		0.7 - 0.9 m		
G	13.19 (0.30) ^{a}	13.68 (0.11) ^{b}	26.87 (0.39) ^{a}	1.22 (0.008) ^{c}
M	9.46 (0.11) ^{a}	27.36 (0.43) ^{a}	36.82 (0.43) ^{a}	1.41 (0.007) ^{ab}
H	22.79 (0.11) ^{a}	8.28 (0.58) ^{b}	31.07 (0.39) ^{a}	1.55 (0.004) ^{a}
PF	14.01 (0.78) ^{a}	13.39 (0.50) b	27.40 (0.23) ^{a}	1.19 (0.010) ^{bc}
		0.0 – 0.9 m		
G	41.07 (0.22) ^{c}	57.93 (0.45) ^{b}	98.99 (0.76) ^{b}	5.05 (0.13) ^{b}
M	53.83 (0.34) ^{b}	120.53 (0.54) ^{a}	174.35 (0.98) ^{a}	6.74 (0.23) ^{a}
H	100.63 (0.76) ^{a}	41.13 (0.12) ^{b}	141.75 (.99) ^{b}	7.79 (0.24) ^{a}
PF	57.53 (0.21) ^{b}	74.15 (0.32) ^{b}	131.68 (0.87) ^{b}	5.46 (0.31) ^{b}

G: Gezira (79 yrs) M: Managil (46 yrs) H: Rahad (22 yrs) PF: Permanent Fallow
Means in columns with the same letter (s) within each soil depth are not significantly different according to LSD at 0.05 level of signficance.

TABLE 7
Total C, organic C, inorganic C and total pools for six depths of the Rain-d Vertisols [(means (standard deviations)].

Cultivation System	Carbon t ha^{-1}			Total N t ha^{-1}
	Organic C	Inorganic C	Total C	
		0.0 - 0.1 m		
NF	10.38 (0.29) [b]	6.02 (0.14) [a]	16.40 (0.24) [a]	1.03 (0.013) [ab]
S-S	12.38 (0.13) [ab]	3.74 (0.08) [a]	16.13 (0.98) [a]	1.07 (0.014) [a]
CS	12.59 (0.19) [a]	3.60 (0.11) [a]	16.19 (0.15) [a]	0.9 (0.011) [b]
		0.1 - 0.2 m		
NF	9.73 (0.27) [b]	5.89 (0.14) [a]	15.62 (0.78) [a]	1.05 (0.005) [a]
S-S	13.74 (0.02) [a]	3.87 (0.14) [a]	17.62 (0.34) [a]	1.01 (0.006) [a]
CS	11.46 (0.05) [ab]	4.61 (0.06) [a]	16.06 (0.88) [a]	0.98 (0.008) [a]
		0.2 - 0.3 m		
NF	15.49 (0.57) [a]	5.57 (0.19) [a]	21.06 (0.75) [a]	0.92 (0.006) [a]
S-S	11.88 (0.47) [a]	5.55 (0.17) [a]	17.43 (0.30) [a]	0.87 (0.002) [a]
CS	11.28 (0.90) [a]	4.29 (0.13) [a]	15.58 (0.48) [a]	0.82 (0.006) [a]
		0.3 - 0.5 m		
NF	24.19 (0.42) [a]	11.23 (0.09) [a]	35.42 (0.34) [a]	1.89 (0.009) [a]
S-S	19.87 (0.26) [a]	10.14 (0.19) [a]	30.02 (0.21) [a]	1.96 (0.016) [a]
CS	26.24 (0.70) [a]	8.38 (0.13) [a]	34.62 (0.76) [a]	1.89 (0.006) [a]
		0.5 - 0.7 m		
NF	16.41 (0.06) [a]	12.87 (0.15) [a]	29.82 (0.93) [a]	1.59 (0.006) [a]
S-S	23.07 (0.87) [a]	10.14 (0.21) [a]	33.21 (0.81) [a]	1.57 (0.003) [a]
CS	24.29 (0.45) [a]	10.01 (0.13) [a]	34.30 (0.49) [a]	1.72 (0.016) [a]
		0.7 - 0.9 m		
NF	17.37 (0.20) [a]	12.99 (0.61) [a]	30.36 (0.58) [a]	1.79 (0.014) [a]
S-S	22.81 (0.48) [a]	10.09 (0.27) [a]	32.91 (0.64) [a]	1.72 (0.014) [a]
CS	21.47 (0.26) [a]	9.25 (0.29) [a]	30.72 (0.48) a	1.67 (0.009) [a]
		0.0 – 0.9 m		
NF	93.57 (0.34) [b]	54.57 (0.21) [a]	148.68 (0.56) [a]	8.27 (0.05) [a]
S-S	103.75 (0.41) [a]	43.53 (0.33) [a]	147.32 (0.65) [a]	8.20 (0.08) [a]
CS	107.33).45) [a]	40.14 (0.23) [a]	147.47 (0.46) [a]	7.98 (0.09) [a]

NF: Natural Forest S-S: Sorghum Sesame rotation CS: Continuous Sorghum
Means in columns with the same letter (s) within each soil depth are not significantly different according to LSD at 0.05 level of signficance

CONCLUSION

Under irrigated Vertisols, OC sequestered in the top 0.0 – 0.90 m profile was 41, 53 and 100 t ha-1 for the long-, medium- and short-term cultivation of Vertisols, respectively. The proportion of total profile (0.0 – 0.9 m) C contributed by inorganic C ranged from 29 to 69%. Long-term cultivation of Vertisols for 79 years had led to a decrease in total C from 132 to 99 t C ha^{-1} (that is, 25% reduction in the form of CO2). Loss from organic C was estimated at 7.2 mt C (27%) with a rate of 0.09 mt C yr^{-1}. Loss from inorganic C was similar to that from organic C indicating that for future stability of soil inorganic C, reliance on ammonium-based fertilisers should be decreased. Cultivation of the same soil order in rain-fed areas had shown to have no reduction in organic C. Since Vertisols in Sudan cover an area more than 20% of the total global Vertisols, and the main agricultural areas belong to this order, their management practice has an important environmental impact. The latter result shows that beside crop rotation, residue management should be adopted to alleviate loss of soil C due to intense soil manipulation.

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REFERENCES

Abdel Nour, H.O. 1999. Implementation of National Forestation Programs in Sudan. A Case Study presented to FAO-Turkey Workshop, Istanbul, Oct. 11-12, 1999.

Ahmed, A.E. 2004. Economic Analysis of the irrigated cotton production constraints in Sudan: Case study Gezira Scheme. *Farming and Rural Systems Economic Series vol 61* edited by Werner Doppler and Siegfried Bauer

Arkley, R.J. 1963. Calculation of carbonate and water movement in soil from climate data. *Soil Sci*. **96**: 239-248.

Ayoub, A.T. 2001. Vertisols Management in the Sudan. In '*The Sustainable Management of Vertisols*'', Edited by JK Syers, Naresuan University, Thailand; F Penning de Vries, IBSRAM, Thailand; P Nyamudeza, DRSS, Zimbabwe.

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of world. *Eur. J. Soil Sci*. **47**: 151-163.

Blake, G.R., K.H. Hartge. 1986. Bulk density. pp 363-382. In "Klute (ed.), *Methods of Soil Analysis*", Part 1: Physical and Mineralogical Methods, American society of Agronomy, Madison, WI.

Blokhuis, W.A. 1993. Vertisols in the Central clay Plain of the Sudan. PhD Thesis, Wageningen Agricultural University, Wageningen.

Bronson, K.F., T.M. Zobeck, T.T. Chua, V. Acosta-Martinez, R.S. van Pelt and J.D. Booker. 2004. Carbon and Nitrogen Pools of Southern High Plains and Grassland Soils. *Soil Sci. Soc. Am. J.* **68**: 1695-1704.

Brye, K.R., E.E. Gbur and D.M. Miller. 2004. Relationships among soil carbon and physiochemical properties of a Typic Albaqualf as affected by years under cultivation. *Comm. Soil Sci. Plant Ana.* **35**: 177-192.

Buraymah, I.M. and R. Webster. 1989. Variation in soil properties caused by irrigation and cultivation in the central Gezira of Sudan. *Soil and Til. Res.* **13**: 57-74.

Dalal, R.C. 2003. The Sustainable Management of Vertisols. *Soil Sci.* **168**: 901-903.

Dawelbeit, M.I. and E.B. Babiker. 1997. Effect of tillage and method of sowing on wheat yield in irrigated Vertisols of Rahad, Sudan. *Soil and Til. Res.* **42**: 127-132.

El-Awad, S.A. 2000. Effects of irrigation interval and tillage systems on irrigated cotton and succeeding crop under heavy clay soil in the Sudan. *Soil and Till. Res.* **55**: 167-173.

Fakki, H.H. 1982. Economic and Management of the Irrigation in the Sudan Gezira Scheme. Ph.D. Thesis, University Hohenheim, Germany. In: Adam, MA (1996) The Policy Impacts on Farmers Production Resource Use Efficiency in the Gezira Irrigated Scheme of Sudan, Vaul Kiel Verlag, Germany.

Hassink, J. 1994. Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. *Soil Biol. Biochem.* **26**: 1221-1231

Hiraika, A.A. 1991. Effects of intensive mechanized crop production and cultivation period on some physical and chemical properties. M.Sc. Thesis, University of Khartoum, Khartoum, Sudan.

Hulugalle, N.R. 2000. Carbon sequesteration in irrigated Vertisols under cotton-based farming systems *Comm. Soil Sci. Plant Ana.* **31**: 645-654.

Jones, T. A. 1958a. A study of carbon-nitrogen ratios on the irrigated soils of the Sudan gezira. *J. Soil Sci.* **9**: 277-279

Jones, T. A. 1958b. Carbon studies on the irrigated soils of the Sudan Gezira. *J. Soil Sc.* **9**: 272-276

Jones, T.A. 1957. Nitrogen studies on the irrigated soils of the Sudan Gezira. *J. Soil Sci.* **19**: 211-224.

Knowles, T.A. and B. Singh. 2003. Carbon storage in cotton soils of northern New South Wales. *Aust. J. Soil Res.* **41**: 889-903.

Kundu, S., M. Singh, K.J. Saha, A. Biswas, A.K. Tripathi and C.L. Acharya. 2001. Relationship between C addition and storage in a Vertisol under soybean-wheat cropping system in sub-tropical central India. *J. Plant Nutr. Soil Sci.* **164**: 483-486.

Lal, R. 1997. Conservation tillage for mitigating greenhouse effect and improving soil quality. *Soil and Till. Res*. **43**: 81-107.

Legros, J.P., P.J. Loveland andM.D.A. Rounsevell. 1994. Soils and climate change-where next? In: *Soil Responses to Climate Change*, pp. 258-266 (eds M.D.A. Rounsevell & P.J. Loveland). NATO ASI Series vol 23, Springer-Verlag, Berlin.

Loeppert, R.H. and D.L. Suarez. 1996. Carbonate and gypsum. In D.L. Sparks *et al*. (eds.). *Methods of Soil Analysis*, Part 3. Chemical Methods. Soil Science Soc Am, Madison, WI.

Mendham, D.S., A.M. O'Conell and T.S. Grove. 2003. Change in soil carbon after land clearing or afforestation in highly weathered lateritic and sandy soils of south-western Australia. *Agri. Ecosyst. Environ*. **95**: 143-156.

Rasmussen, P.E. and L. Albrecht. 1998. Crop management effects on organic carbon in Semi-arid pacific North west soils. In: R.Lal., J.M. Kimble, R.F. Follet, and B.A. Stewart: *Management of Carbon Sequetstration in Soil*. CRC Press, Boca Raton, New York, p. 209-219.

Salih, A.A., H.M. Babiker and S.A.M. Ali. 1998. Preliminary observations on effects of tillage on soil physical properties cotton growth and yield in Gezira Scheme, Sudan. *Soil and Till. Res*. **46**: 187-191

SAS. 1985. SAS Users Guide Statistics, 5th edn, SAS Institute, Cary, NC, U.S.A.

Soil Survey Staff. 1996. Keys to Soil Taxonomy, 7th edition. United States Department of Agriculture, Washington, D.C.

Wani, S.P., P. Pathak, L.S. Jangawad, H. Eswaran and P. Singh. 2003. Improved management of Vertisols in the semiarid tropics for increased productivity and soil carbon sequestration. *Soil Use Manag*. **19**: 217-222.

Wickens, G.E. 1991. Natural Vegetation. In: Graig G.M. (ed.), The Agriculture of the Sudan. Oxford University Press, London pp 54-67.

World Bank. 2000. Sudan - Options for the Sustainable Development of the Gezira Scheme Sector Report No. 20398-Su.