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Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa

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Abstract

Tillage, organic resources and fertiliser effects on soil carbon (C) dynamics were investigated in 2000 and 2001 in Burkina Faso (West Africa). A split plot design with four replications was laid-out on a loamy-sand Ferric Lixisol with till and no-till as main treatments and fertiliser types as sub-treatments. Soil was fractionated physically into coarse (0.250–2 mm), medium (0.053–0.250 mm) and fine fractions (< 0.053 mm). Particulate organic carbon (POC) accounted for 47–53% of total soil organic carbon (SOC) concentration and particulate organic nitrogen (PON) for 30–37% of total soil nitrogen concentration. The POC decreased from 53% of total SOC in 2000 to 47% of total SOC in 2001. Tillage increased the contribution of POC to SOC. No-till led to the lowest loss in SOC in the fine fraction compared to tilled plots. Well-decomposed compost and single urea application in tilled as well as in no-till plots induced loss in POC. Crop N uptake was enhanced in tilled plots and may be up to 226 kg N ha^{-1} against a maximum of 146 kg N ha^{-1} in no-till plots. Combining crop residues and urea enhanced incorporation of new organic matter in the coarse fraction and the reduction of soil carbon mineralisation from the fine fraction. The PON and crop N uptake are strongly correlated in both till and no-till plots. Mineral-associated N is more correlated to N uptake by crop in tilled than in no-till plots. Combining recalcitrant organic resources and nitrogen fertiliser is the best option for sustaining crop production and reducing soil carbon decline in the more stabilised soil fraction in the semi-arid West Africa.

Keywords: Organic resources; Particulate organic matter; Tillage; Soil physical fractionation; Crop N uptake; Burkina Faso

1. Introduction

Soils in semi-arid West Africa are prone to degradation because of their inherently low fertility (Breman and Bationo, 1999; Stroosnijder and Van Rheenen, 2001). Soil degradation follows inappropriate cropping systems and overexploitation of the soils. There is a great need for a tool that predicts early trends in soil degradation and for an appropriate soil management option that maintains soil quality. Soil quality is strongly linked to soil organic matter (SOM), which influences soil physical, biological and chemical soil properties and the stock of plant nutrients. The SOM consists of partially decayed plant

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residues that are no longer recognisable as plant material, living organisms, by-products of the decomposition process and humus (Paul and Clark, 1996). Recent developments in SOM studies suggest that particulate organic matter (POM) is a good indicator of soil quality and is more sensitive to soil management practices such as tillage and fertilisation than total SOM concentration (Bayer et al., 2001; Chan, 2001; Chan et al., 2002). The POM consists of soil organic carbon (SOC) in the 0.053–2 mm fraction. The C concentration of this fraction is referred to as particulate organic carbon (POC) (Cambardella and Eliott, 1992).

Vanlauwe et al. (1998) showed that the quality of organic amendments and their decomposition is an important factor that affects various pools of SOM. However, how organic resource quality affects these various pools is not well documented in semi-arid West Africa. In addition, Wander and Yang (2000) reported that the manner in which residues are incorporated into the soil can also influence the fate of total SOC. They showed that SOC concentration increases at the surface in no-till soils as a result of residue concentration. In some cases, decay rates of residues placed at the soil surface are slower than when residues are incorporated. In other cases, surface-placed residues decay rapidly where moisture, nutrient status and soil fauna activity are non-limiting (Mando and Stroosnijder, 1999; Mando et al., 1999). A study on SOM dynamics was conducted in the central plateau of Burkina Faso, West Africa. The objective of the study was to assess the dynamics of SOM with different types of fertilisers and to determine the best option, which sustain SOM and crop production. We anticipated that early change in POM may give insight in soil carbon dynamics.

We also hypothesised that positive change in POM may be observed with the combination of organic and inorganic inputs. To test this hypothesis, carbon and nitrogen dynamics across different soil management options and fertiliser input were investigated for two consecutive cropping years.

2. Methodology

2.1. Site description

The experiment was conducted on a Ferric Lixisol with a loamy-sand texture and low SOM and nutrient concentrations. Characteristics of the topsoil (0–10 cm) are presented in Table 1. The study was conducted at Gampela, a village located in the central plateau of Burkina Faso (Fig. 1) between 12°25′N, 1°21′W during two successive cropping years of 2000 and 2001. The climate is Soudano-Sahelian, and the rainfall is monomodal and typically occurs for 4 months between June and September. It is irregularly distributed in time and space. The mean annual rainfall is 773 mm (based on the last 97 years).

Table 1
Characteristics of the topsoil (0–10 cm) of a Ferric Lixisol at Gampela, Burkina Faso

Soil properties	Values
Clay (%)	6 ± 1.8
Silt (%)	42 ± 2.4
Sand (%)	52 ± 3.7
Carbon (g kg^{-1})	4.7 ± 0.5
Nitrogen (g kg^{-1})	0.4 ± 0.1
Phosphorus (mg kg^{-1})	55 ± 12
Potassium (mg kg^{-1})	304 ± 23
Exchangeable calcium (μmol kg^{-1})	0.87 ± 0.21
Exchangeable magnesium (μmol kg^{-1})	0.43 ± 0.06
Exchangeable potassium (μmol kg^{-1})	0.17 ± 0.09
Exchangeable sodium (μmol kg^{-1})	0.06 ± 0.01
pH (H_2O)	6.6 ± 0.3
pH (KCl)	4.9 ± 0.3

±Standard deviation.

2.2. Experimental design

The experiment was a split plot design with three replications (blocks) with tillage and no-till as main treatments. The plots were 19 m × 11 m and 5 m apart. The size of the sub-plots was 5 m × 4 m separated by a guard row of 1 m. The blocks were separated by an alley of 2 m. The sub-treatments consisted of C: control (0 N), U: urea (40 kg N ha^{-1}), U80: urea (80 kg N ha^{-1}), SD: sheep dung (40 kg N ha^{-1}), SD + U: sheep dung (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}), S: maize straw (40 kg N ha^{-1}), CO: compost (40 kg N ha^{-1}), S + U: maize straw (40 kg N ha^{-1}) + urea (40 kg N ha^{-1}). The compost was made by aerobic composting in heaps (Ouédraogo et al., 2001). Triple super phosphate (TSP) was applied at a rate of 15 kg P ha^{-1} every year to avoid phosphorus limitation. Chemical properties and application rate of the organic amendments applied during the 2 years are shown in Table 2.

2.3. Crop and soil management

An improved sorghum (*Sorghum bicolor* L. Moench) variety (SARIASO14) was sown in all plots at a rate of 31,250 seedling ha^{-1} during the two cropping seasons. Organic materials and fertilisers were applied every year before sowing and before tilling the plots. Animal power was used for the tillage (12 cm depth). In no-till plots, organic materials and urea were applied at the soil

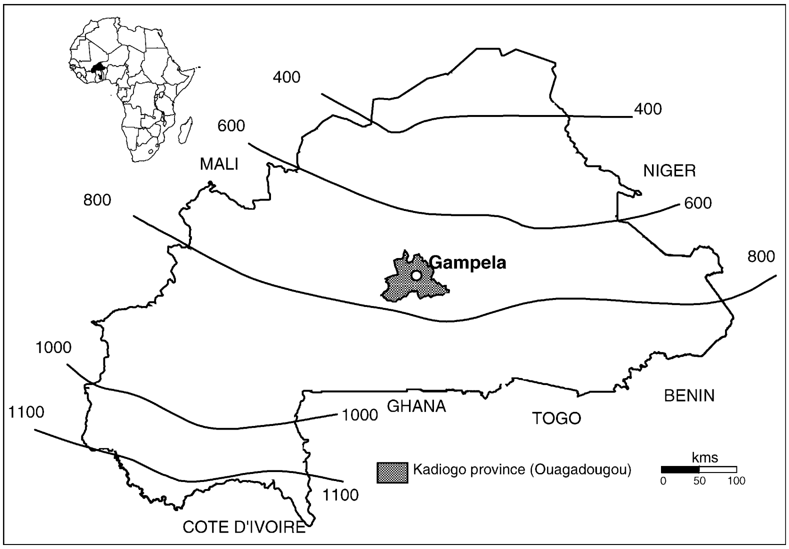

Fig. 1. Experimental site location. The isohyets depict annual mean rainfall in millimeter.

surface. During the growing period the plots were manually weeded twice. Sorghum was harvested after 4 months.

2.4. Soil fractionation and chemical analysis

Composite (three sub-samples) soil samples (0–10 cm) from each treatment were collected during 2000 and 2001 at 2 months after fertilisation. Samples were air-dried at room temperature, ground and passed through a 2-mm sieve.

The technique of determining particle size distribution involving the use of sodium hexametaphosphate as dispersant leads to the dissolution of organic carbon and can, therefore, be a source of errors (Feller, 1979; Chan, 2001). An alternative method was proposed by Feller (1979) based on physical dispersion. This method proved to be accurate and avoids carbon dissolution. Hundred grams of soil was dispersed in 300 ml of distilled water containing three glass bullets and shaken for 1 h in an end to end shaker. The soil suspension was then wet-sieved through 2, 0.250 and 0.053 mm sieves to separate coarse (F1) (0.250–2 mm), medium (F2) (0.053–0.250 mm) and fine fractions (F3) (< 0.053 mm). The coarse fraction (F1) is separated into two sub-fractions: recognisable plant material consisting of plant debris and roots were gently separated as free organic matter (fOM) and the remaining is classified as organic matter associated with soil particles (aOM). Different soil fractions were dried in a forced-air oven at 60 °C, weighed to assess soil mass, ground with a mortar and analysed for total SOC and N concentrations. The C and N pools in the different fractions were calculated considering the mass of soil of this granulometric fraction and total C and N concentrations. Particulate organic carbon and nitrogen (POC and

Table 2
Chemical properties and application rate of organic materials applied in 2000 and 2001 at Gampela, Burkina Faso

	2000			2001		
	Maize straw[a]	Sheep dung[a]	Compost[a]	Maize straw	Sheep dung	Compost
Total quantity (kg ha^{-1})	5195	2614	4819	6780	2484	5714
Carbon (C) (kg ha^{-1})	2343	659	415	3661	993	1034
Nitrogen (N) (kg ha^{-1})	40	40	40	40	40	40
Phosphorus (P) (%)	0.18	0.33	0.18	0.08	0.19	0.14
Potassium (K) (%)	1.20	1.20	0.73	1.25	1.55	0.40
Lignin (L) (%)	0.16	0.16	0.91	0.14	0.28	0.7
C/N ratio	59	17	10	91	25	25
L/N ratio	0.21	0.1	1.1	0.24	0.17	1.0

[a] Organic resources.

PON) were calculated as the difference in C and N passing through 0.053 mm sieve and that obtained from the corresponding whole soil sample expressed on an oven-dried whole soil basis. Therefore, in the present study we distinguished particulate organic matter, carbon (POC) and nitrogen (PON) from total amount of SOM, SOC and nitrogen (TON). The total mineral-associated nitrogen (MAN) is the fraction of soil nitrogen in the <0.053 mm fraction. POC can also be considered as the sum of SOC in F1 and F2.

The method based on dispersion with the sodium hexametaphosphate can lead to a loss of 5–18% of SOC (Chan, 2001). The recovery in the method used was 99%. The SOC was measured by the Walkley–Black Method and total N by the colorimetry after digestion by the Kjeldhal method.

Total N in aboveground plant material was measured in 2001. A composite sample (three sub-samples) of whole plant material was taken at flowering, dried at room temperature, milled and analysed for total N. Total N uptake was corrected by adding the N post-anthesis N uptake fraction for sorghum derived from the model developed by Van Duivenboden et al. (1996).

2.5. Data calculation and analyses

The calculation aims to highlight the magnitude of the variation of SOC in the different fractions as compared to the change in total SOC from 2000 to 2001.

Changes in each soil fraction from 2000 to 2001 is expressed in % of the change of soil total carbon and calculated as follow:

$$\text{SOC change (\%)} = \left(\frac{\text{CF}_{2001} - \text{CF}_{2000}}{\text{Csoil}_{2001} - \text{Csoil}_{2000}}\right) \times 100.$$

where CF_{2001} is the SOC in soil fraction in 2001; CF_{2000} the SOC in soil fraction in 2000; Csoil_{2001} the soil total organic carbon in 2001; Csoil_{2000} is the soil total organic carbon in 2000.

The ANOVA was computed for 2000 and 2001 to assess change in SOC.

3. Results

3.1. Carbon concentrations in soil fractions and in the bulk soil

Total SOC and N dynamics have been studied by Ouédraogo (2004). Therefore, the present study focused on SOC in different soil fractions. SOC concentrations in the three soil fractions are shown in Table 3. The fine fraction had the highest SOC concentration, which accounted for 47–53% of the total soil carbon stock against 39–43% in the coarse fraction and 8–10% for the medium fraction.

3.2. Carbon concentration in the coarse fraction (F1) (0.250–2 mm)

In 2000, in tilled plots, SOC was the highest in SD + U with significant differences compared to S, SD and the control but not significantly different from U, U80, CO and S + U (Table 3). In no-till plots, the lowest SOC was observed in U and U80 with significant differences compared to the control and SD + U but not different from the other treatments.

In 2001, in tilled plots, the highest SOC concentration was observed in S + U but it did not differ significantly from the other treatments (Table 3). No significant differences were observed among treatments in no-till plots.

In 2000, the average contribution of fOC (plant debris and roots) to SOC in F1 was 28% in tilled plots and 23% in no-till plots. In tilled plots, the highest contribution of fOC was observed in S + U (39%) and significantly different from the other treatments except in U (Fig. 2a). The lowest fOC was observed in CO (14%). In no-till plots, the highest fOC was observed in SD with significant differences compared to other treatments. Among the other treatments, SOC in F1 was significantly higher in SD + U than in U but did not differ from the other treatments. The highest proportion of fOC in the no-till plots was noted in SD (54%) followed by U80 (30%). The aOC was significantly higher in SD + U compared to other treatments except in CO in tilled plots. In no-till plots, the aOC was significantly lower in SD compared to S, CO, C and SD + U but did not differ from the other treatments in 2000.

In 2001, the average contribution of fOC to SOC in F1 was 27% in tilled plots and 25% in no-till plots. In tilled plots, fOC was the highest in U and S + U with significant differences compared to other treatments (Fig. 2b). In no-till plots, fOC was significantly higher in U80, S + U and SD + U compared to SD but not different from other treatments. In tilled as well as in no-till plots fOC contribution to SOC in F1 was the highest in S + U, U80 and U (30–43%). No significant differences in aOC were observed among the treatments in tilled as well as in no-till plots. ANOVA shows that the year, tillage and fertilisation affected fOC while their interactions were also significant. Fertilisation also affected total SOC, and SOC in F1 and aOC were significantly different between the years (Table 4).

Table 3
SOC (g kg^{-1}) in three soil fractions for till and no-till conditions under various fertilisation regimes in 2000 and 2001 at Gampela, Burkina Faso

Fertilisation	Tillage	2000			2001		
		F1	F2	F3	F1	F2	F3
Maize straw	T	1.82^{a}	0.67^{ab}	2.67^{ab}	1.99^{a}	0.43^{ab}	2.32^{a}
	NT	2.68^{AB}	0.52^{A}	2.65^{AB}	1.69^{A}	0.49^{B}	2.57^{AB}
Sheep dung	T	2.22^{a}	0.65^{ab}	2.66^{ab}	2.22^{a}	0.45^{ab}	2.54^{a}
	NT	2.49^{AB}	0.71^{AB}	2.93^{B}	1.75^{A}	0.37^{AB}	2.42^{AB}
Compost	T	2.75^{b}	0.48^{a}	2.27^{a}	1.87^{a}	0.36^{a}	2.32^{a}
	NT	2.55^{AB}	0.39^{A}	2.26^{A}	1.69^{A}	0.44^{AB}	2.23^{A}
Urea	T	2.52^{ab}	0.74^{ab}	2.74^{ab}	1.85^{a}	0.33^{a}	2.64^{a}
	NT	2.03^{A}	0.45^{AB}	2.61^{AB}	1.75^{A}	0.45^{AB}	2.39^{AB}
Control	T	2.25^{a}	0.69^{ab}	2.69^{ab}	2.07^{a}	0.46^{ab}	2.77^{a}
	NT	2.83^{B}	0.51^{AB}	2.58^{AB}	1.64^{A}	0.33^{A}	2.79^{BC}
Urea 80	T	2.46^{ab}	0.60^{ab}	2.79^{b}	2.03^{a}	0.43^{ab}	2.47^{a}
	NT	2.35^{A}	0.45^{AB}	2.64^{AB}	1.61^{A}	0.34^{A}	2.53^{AB}
Maize straw + urea	T	2.45^{ab}	0.91^{b}	2.98^{b}	2.48^{a}	0.50^{b}	2.55^{a}
	NT	2.40^{AB}	0.63^{AB}	2.70^{AB}	1.39^{A}	0.39^{AB}	3.11^{C}
Sheep dung + urea	T	3.17^{b}	0.67^{ab}	2.80^{b}	2.13^{a}	0.47^{ab}	2.66^{a}
	NT	3.14^{B}	0.94^{B}	2.95^{B}	2.13^{A}	0.51^{B}	2.75^{BC}

$LSD_{0.05}$ test: Upper case (superscript letters) compares treatment in tilled plots, lower case (superscript letters) compares treatments in no-till plots. Treatments with the same letter in the same column are not significantly different at a level of 5%. F1: SOC in 0.250–2 mm, F2: SOC in 0.053–0.250 mm; F3: SOC in <0.053 mm, T: till, NT: no-till, maize straw: 40 kg N ha^{-1}, sheep dung: 40 kg N ha^{-1}, compost: 40 kg N ha^{-1}, urea: 40 kg N ha^{-1} and urea 80: urea (80 kg N ha^{-1}).

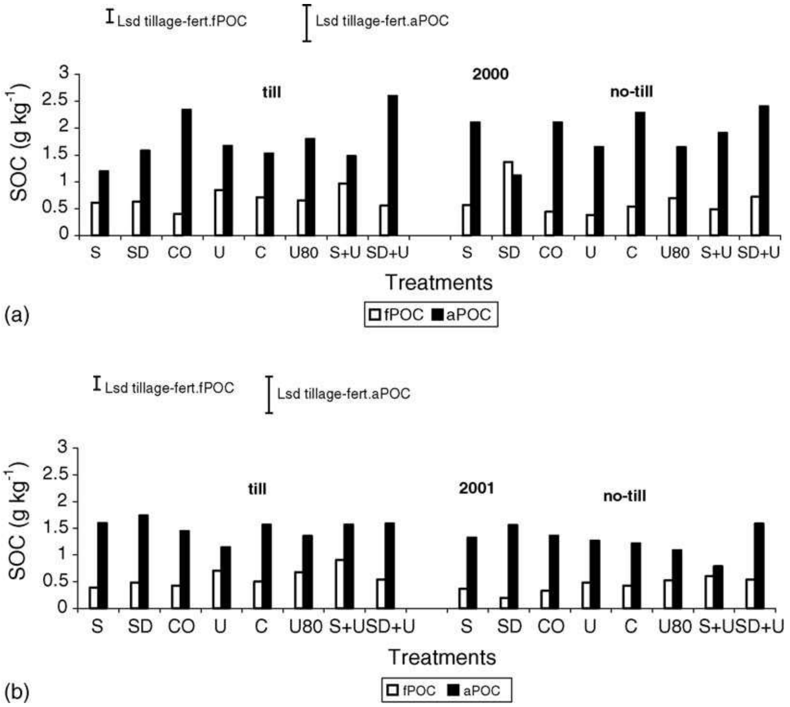

Fig. 2. Proportion of free particulate organic carbon (fOC) and POC associated with soil particles (aOM) in the coarse fraction (F1) in 2000 (a) and 2001 (b) at Gampela, Burkina Faso. S, maize straw (40 kg N ha^{-1}); SD, sheep dung (40 kg N ha^{-1}); CO, compost (40 kg N ha^{-1}); U, urea (40 kg N ha^{-1}); U80, urea (80 kg N ha^{-1}); C, control (0 N).

Table 4
Repeated measurements ANOVA for total SOC, soil carbon in soil fractions and mineral-associated nitrogen (MAN) from 2000 to 2001

Source of variation	Total SOC	F1			F2	F3	POC	PON	MAN
		Total F1	fOC	aOC					
Year	<0.001	<0.001	0.002	0.004	<0.001	0.035	<0.001	0.006	<0.001
Tillage	0.289	0.264	0.031	0.973	0.102	0.803	0.116	0.246	0.034
Fertilisation	0.036	0.123	0.012	0.103	0.097	0.012	0.073	0.238	0.222
Year × tillage	0.271	0.082	0.081	0.368	0.239	0.390	0.128	0.551	0.282
Year × fertilisation	0.894	0.820	0.004	0.465	0.190	0.449	0.854	0.064	0.995
Tillage × fertilisation	0.720	0.715	0.011	0.839	0.330	0.908	0.515	0.395	0.849
Year × tillage × fertilisation	0.717	0.706	0.036	0.659	0.242	0.251	0.597	0.207	0.692

F1: 0.250–2 mm fraction, fOC: free organic carbon in F1, aOC: mineral-associated carbon in F1, F2: SOC in 0.053–0.250 mm fraction, F3: SOC in < 0.053 mm fraction, POC: particulate organic carbon, PON: particulate organic nitrogen, MAN: mineral-associated organic nitrogen.

3.3. Carbon concentration in the medium fraction (F2) (0.053–0.250 mm)

In 2000, the highest SOC in F2 in tilled plots was noted in S + U, significantly different from CO but not from the other treatments. In no-till plots, the highest SOC in F2 was noted in SD + U with significant differences compared to S and CO but not from the other treatments.

In 2001, in tilled plots, SOC in F2 was significantly higher in S + U compared to U and CO but it did not differ significantly from the other treatments. In no-till plots, SOC in F2 was significantly higher in SD + U and S with significant differences compared to the control and U80, but not from the other treatments. The SOC in F2 was significantly different between years. The effect of fertilisation was marginally significant ($P = 0.097$).

3.4. Carbon concentration in the fine fraction (F3) (<0.053 mm)

In tilled plots, SOC in F3 was significantly higher in S + U compared to CO but did not differ significantly from the other treatments in 2000. No significant differences were observed among the other treatments.

In 2001, in tilled plots, no significant differences in SOC in F3 were observed between the treatments. In no-till plots, the highest SOC in F3 was observed in S + U with significant differences compared to other treatments except SD + U and the control. Fertilisation significantly affected SOC in F3 while differences between years were also significant.

3.5. Particulate organic carbon and nitrogen concentrations

The average POC accounted for about 53% of total SOC in 2000 and 47% in 2001 (Table 5). In 2000, in tilled plots, POC was significantly higher in SD + U than CO and S but not different from other treatments. In no-till plots, POC was the significantly higher in SD + U than CO, U, U80 and S + U but it did not differ from S, SD and the control. In 2001, no significant difference in POC was observed between the treatments in tilled plots. In no-till plots, POC was significantly higher in SD + U than S + U, U80 and the control.

The PON data are summarised in Table 6. The mean contribution of PON to total soil N concentration was 30 and 37%, respectively, in 2000 and 2001, implying a mean decrease in the contribution of the mineral-associated nitrogen (MAN) to total N from 70% in 2000 to 63% in 2001. In tilled plots, PON was the highest in S + U, significantly different from CO, U80 and the control. In no-till plots, PON was significantly higher in SD + U than other treatments except SD and S + U. In 2001, in tilled plots, the highest PON was observed in SD and S+U, significantly different from other treatments. The lowest PON was observed in U, U80 and SD + U. POC and PON were significantly different between years.

3.6. The C:N ratios of particulate- and mineral-associated organic matter fractions

The C:N ratios of POM-associated fractions were higher in 2000 than in 2001 with a mean value of 19.8 and 16.7, respectively, in 2000 and 2001 compared to 7.2 and 10.9 in mineral-associated organic matter fraction (Table 7). In 2001, tillage and fertilisation did not affect the POM C:N ratio and no significant differences were observed among the treatments. No significant impact of fertilisation and tillage was observed on mineral-associated organic matter fraction C:N ratio in 2000 and 2001.

Table 5
Particulate organic carbon (POC) for tillage and no-till conditions under various fertilisation regimes at 2 months after fertilisation in 2000 and 2001

Treatments		2000			2001		
Fertilisation	Tillage	TOC (g kg^{-1})	POC (g kg^{-1})	% C total in POC	TOC (g kg^{-1})	POC (g kg^{-1})	% C total in POC
Maize straw	T	5.2^{a}	2.5 (0.6)^{a}	48.2	4.7^{a}	2.4 (0.2)^{a}	51.1
	NT	5.9^{AB}	3.2 (0.6)^{AB}	54.2	4.8^{AB}	2.2 (0.1)^{AB}	45.9
Sheep dung	T	5.5^{a}	2.9 (0.6)^{ab}	51.9	5.2^{ab}	2.2 (0.4)^{a}	51.4
	NT	6.1^{B}	3.2 (0.4)^{AB}	52.3	4.5^{A}	2.1 (0.3)^{AB}	46.8
Compost	T	5.5^{a}	3.2 (1.0)^{a}	58.7	4.6^{a}	2.2 (0.8)^{a}	49.0
	NT	5.2^{A}	2.9 (0.1)^{A}	56.5	4.3^{A}	2.1 (0.5)^{AB}	48.9
Urea	T	6.0^{ab}	3.3 (0.1)^{ab}	54.3	4.8^{a}	2.2 (0.7)^{a}	45.2
	NT	5.1^{A}	2.5 (0.8)^{A}	48.8	4.6^{A}	2.2 (0.2)^{AB}	47.8
Control	T	5.6^{a}	2.9 (0.4)^{ab}	52.1	5.3^{ab}	2.5 (0.6)^{a}	47.8
	NT	5.9^{AB}	3.3 (0.7)^{AB}	56.5	4.8^{AB}	1.9 (0.2)^{A}	41.3
Urea 80	T	5.8^{ab}	3.1 (0.6)^{ab}	52.3	4.9^{ab}	2.5 (0.3)^{a}	49.9
	NT	5.4^{AB}	2.8 (0.8)^{A}	51.5	4.5^{A}	1.9 (1.0)^{A}	43.4
Maize straw + urea	T	6.3^{b}	3.4 (0.9)^{ab}	53.0	5.5^{b}	2.9 (0.1)^{a}	53.8
	NT	5.7^{AB}	3.0 (0.6)^{A}	52.8	4.9^{AB}	1.8 (0.7)^{A}	36.4
Sheep dung + urea	T	6.6^{b}	3.8 (0.5)^{b}	57.8	5.3^{ab}	2.6 (0.6)^{a}	49.4
	NT	7.0^{C}	4.1 (1.0)^{B}	58.0	5.4^{B}	2.6 (0.5)^{B}	48.9

LSD$_{0.05}$ test: Upper case (superscript letters) compares treatment in tilled plots, lower case (superscript letters) compares treatments in no-till plots; standard deviation within parenthesis. Treatments with the same letter in the same column are not significantly different at a level of 5%. Treatment explanations as in Table 3.

Table 6
PON at 2 months after fertilisation in 2000 and 2001 at Gampela, Burkina Faso

Treatments		2000			2001		
Fertilisation	Tillage	TON (g kg^{-1})	PON (g kg^{-1})	% total N in PON	TON (g kg^{-1})	PON (g kg^{-1})	% total N in PON
Maize straw	T	0.48^{a}	0.18 (0.05)^{ab}	38.1	0.37^{a}	0.16 (0.02)^{ab}	43.2
	NT	0.52^{A}	0.14 (0.03)^{A}	26.8	0.41^{AB}	0.18 (0.02)^{B}	44.0
Sheep dung	T	0.54^{ab}	0.19 (0.04)^{ab}	35.8	0.39^{ab}	0.19 (0.05)^{b}	47.4
	NT	0.57^{A}	0.21 (0.05)^{AB}	37.3	0.39^{AB}	0.14 (0.07)^{AB}	35.4
Compost	T	0.51^{ab}	0.14 (0.05)^{a}	27.1	0.36^{a}	0.14 (0.07)^{a}	38.2
	NT	0.47^{A}	0.11 (0.02)^{A}	23.7	0.40^{AB}	0.16 (0.05)^{AB}	40.9
Urea	T	0.57^{ab}	0.18 (0.05)^{ab}	31.9	0.38^{a}	0.13 (0.05)^{a}	31.9
	NT	0.58^{A}	0.16 (0.04)^{A}	26.9	0.36^{A}	0.14 (0.3)^{AB}	39.3
Control	T	0.53^{ab}	0.17 (0.05)^{a}	31.9	0.41^{ab}	0.17 (0.04)^{ab}	41.0
	NT	0.58^{A}	0.13 (0.04)^{A}	23.2	0.37^{A}	0.10 (0.2)^{A}	27.7
Urea 80	T	0.51^{ab}	0.15 (0.03)^{a}	29.9	0.40^{ab}	0.15 (0.06)^{a}	39.1
	NT	0.58^{A}	0.13 (0.05)^{A}	22.6	0.38^{A}	0.11 (0.2)^{A}	29.2
Maize straw + urea	T	0.59^{b}	0.22 (0.07)^{b}	37.3	0.45^{b}	0.19 (0.06)^{b}	40.9
	NT	0.67^{B}	0.18 (0.05)^{AB}	27.5	0.40^{AB}	0.11 (0.3)^{A}	26.6
Sheep dung + urea	T	0.59^{b}	0.18 (0.04)^{ab}	30.1	0.38^{a}	0.14 (0.05)^{a}	37.3
	NT	0.66^{B}	0.27 (0.02)^{B}	41.1	0.45^{B}	0.16 (0.7)^{AB}	36.2

LSD$_{0.05}$ test: Upper case (superscript letters) compares treatments in tilled plots, lower case (superscript letters) compares treatments in no-till plots; standard deviation between parenthesis. Treatments with the same letter in the same column are not significantly different at a level of 5%. Treatment explanations as in Table 3.

Table 7
C:N ratios of POM-fractions (>0.053 mm) and mineral-associated organic matter fractions (<0.053 mm) in 2000 and 2001 in Gampela, Burkina Faso

Treatments		C:N ratio 2000		C:N ratio 2001	
Fertilisation	Tillage	POM	SOM < 0.053	POM	SOM < 0.053
Maize straw	T	13.6^{a}	8.9^{a}	14.9^{a}	10.9^{a}
	NT	22.9^{AB}	7.0^{A}	11.8^{A}	11.5^{A}
Sheep dung	T	14.8^{a}	7.7^{a}	14.3^{a}	12.2^{a}
	NT	15.1^{A}	8.3^{A}	15.6^{A}	9.7^{A}
Compost	T	23.4^{a}	6.1^{a}	16.0^{a}	10.3^{a}
	NT	26.4^{B}	6.4^{A}	13.0^{A}	9.4^{A}
Urea	T	17.8^{a}	7.1^{a}	17.8^{a}	10.1^{a}
	NT	15.9^{A}	6.1^{A}	15.6^{A}	10.9^{A}
Compost	T	17.3^{a}	7.4^{a}	14.9^{a}	11.3^{a}
	NT	24.9^{AB}	5.8^{A}	19.1^{A}	10.4^{A}
Urea 80	T	20.1^{a}	7.7^{a}	15.9^{a}	10.2^{a}
	NT	21.4^{AB}	5.9^{A}	17.5^{A}	9.4^{A}
Maize straw + urea	T	15.3^{a}	8.1^{a}	16.1^{a}	9.5^{a}
	NT	16.5^{AB}	5.6^{A}	16.7^{A}	10.5^{A}
Sheep dung + urea	T	21.6^{a}	6.8^{a}	18.2^{a}	11.1^{a}
	NT	15.0^{A}	7.5^{A}	16.3^{A}	9.6^{A}

$LSD_{0.05}$ test: Upper case (superscript letters) compares treatments in tilled plots, lower case (superscript letters) compares treatments in no-till plots. Treatment explanations as in Table 3.

3.7. Dynamics of SOC in soil fractions from 2000 to 2001

The dynamics of SOC in soil fractions expressed in percent of the change in TOC from 2000 to 2001 are summarised in Fig. 3. From 2000 to 2001, SOC in F1 contributed positively to TOC change in S (40%) and S + U (4%) in tilled plots. SOC in F1 contributed negatively to TOC change in CO, U, C, U80 and SD + U. In no-till plots, SOC in F1 was the most responsible for the decline in SOC in all treatments with the highest impact in S + U, C, CO and S.

The SOC in F2 contributed negatively to TOC change in all the treatments in tilled as well as in no-till plots except in CO in no-till plots, the effect being more important in tilled plots than in no-till plots. The contribution of F3 to TOC change was negative in all treatments except in the control (+24%) in tilled plots and was more pronounced in S and S + U although the addition of urea in S + U reduced the effect compared to

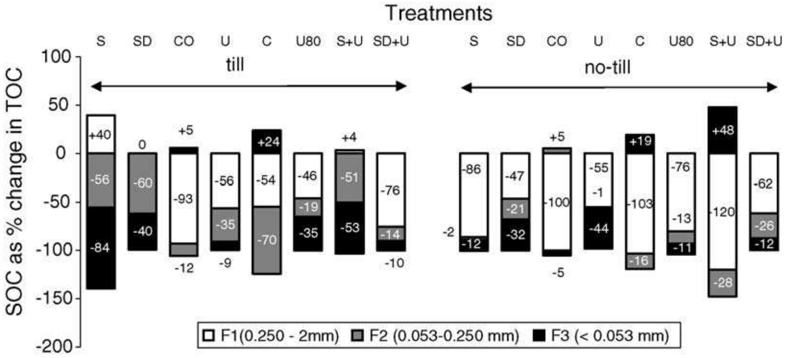

Fig. 3. Dynamics of soil carbon in soil fractions as a percentage change in soil total carbon concentration from 2000 to 2001, 2 months after fertilisation at Gampela, Burkina Faso. Treatment explanation as in Fig. 2.

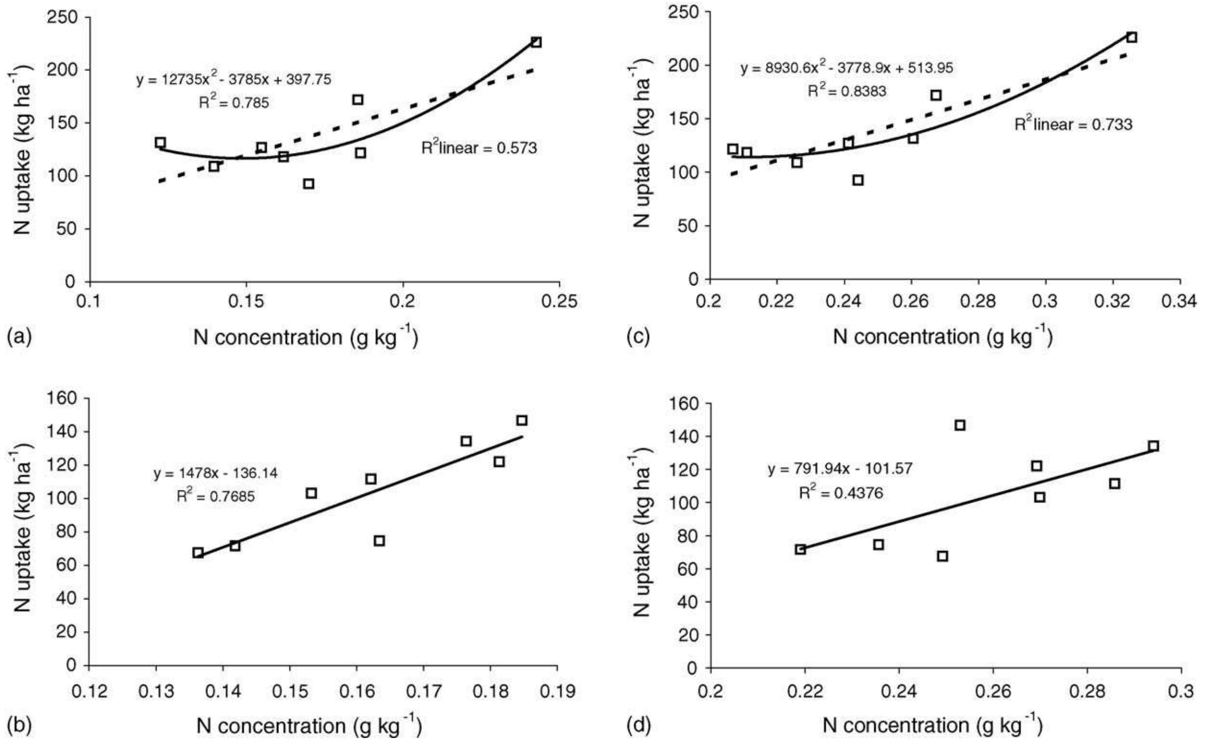

Fig. 4. Relations between crop nitrogen uptake and PON in tilled plots (a), in no-till (b) and mineral-associated nitrogen (MAN) in tilled plots (c) and in no-till plots (d) in 2001 at Gampela, Burkina Faso.

S. Addition of urea in SD + U also reduced the decline compared to SD. The SOC decline in F3 was higher in U80 compared to U.

In no-till plots, the highest negative contribution of SOC in F3 to TOC change was observed in U and SD. The negative contribution of F3 to TOC change in S shifted to positive in S + U. The SOC in F3 decline was reduced in SD + U compared to SD and in U80 compared to U in no-till plots. No significant change in TOC due to SOC in F3 was observed in the compost treatment. Considering that POC consists of the sum of SOC in F1 and F2 in tilled as well as in no-till plots, the decline in POC was mostly responsible for the decrease in TOC from 2000 to 2001.

3.8. *PON, MAN and crop performance relationships*

Correlation between TON, PON, MAN and SOC in the three fractions with crop nitrogen uptake was highest with PON and MAN (Fig. 4). Crop N uptake was higher in tilled plots (Fig. 4a and c) than in no-till plots (Fig. 4b and d). Crop N uptake was more correlated with MAN in tilled plots than in no-till plots.

4. Discussion

The POC contributed approximately 53% of TOC in 2000 and 47% in 2001. These results are consistent with those reported by Feller (1979) and Feller et al. (1983) for West African sandy soils (57 and 51%, respectively). Soil carbon, during the humification process, passes successively through the coarse to the fine fractions and this explains the lower C:N ratio of the mineral-associated organic matter fraction compared to the POM fraction (Feller et al., 1987; Vanlauwe et al., 1998). The increase in the C:N ratios of mineral-associated organic matter from 2000 to 2001 is obviously due to a depletion of PON. The decrease in POM C:N ratio from 2000 to 2001 may be attributed to the contribution of root-derived nitrogen which increased in the coarse fraction.

The dynamics of SOC in the different soil fractions showed that SOC in the coarse fraction was more sensitive to the management practices. Shang and Tiessen (1998) reported that in semi-arid soils, a large proportion of SOM was in a form of coarse, unprocessed plant debris in the sand fraction. They indicated that such material is more easily broken down after (tillage) disturbance.

Increasing the inputs of cropping systems was found to increase POC over time (Bowman et al., 1999) and this may explain the increase in POC in the coarse fraction in tilled plots compared to no-till plots in 2001. As reported by Richter et al. (1990), root-derived SOC is a dominant factor in the SOC balance in tilled plots. This is confirmed in our study by the higher contribution of fOC in tilled than in no-till plots. Indeed, in many cases tillage improves crop performance in semi-arid West Africa and induces high root biomass input to soil.

Strong correlation between PON and crop N uptake in both tilled and no-till plots confirms that nitrogen in POM mostly affects crop performance. Similar results were reported by Vanlauwe et al. (2000), and this trend is likely due to the higher mineralisation rate of POM (Vanlauwe et al., 1999) than that of the mineral-associated SOC, which is partly protected by clay and silt. The N uptake by the crop from the MAN was higher in tilled than in no-till plots and may be explained by POM exposure to mineralisation after aggregates were disrupted by tillage. The non-linear relationship in tilled plots was likely due to the different effect of tillage on crop N uptake efficiency, which may vary with the type of fertilisation. The significant correlation between MAN and crop uptake suggests that part of the N taken up is derived from this fraction and is likely in a situation of N deficiency.

Our study suggests that total SOC maintenance in S + U with tillage is related to an enhanced incorporation of new organic material in the coarse fraction (as fOC in S + U was in general higher than in S), probably due to an enhanced breakdown of maize straw, an increased production of root biomass and the reduction of SOC loss from the fine fraction. Indeed, from 2000 to 2001, the tillage impact in depressing SOC in F3 was enhanced with single use of maize straw. A high negative contribution of F1 to TOC change in no-till plots from 2000 to 2001 in S + U is likely due to the decrease of aOM, as fOM and SOC in F3 increased from 2000 to 2001. This is probably due to N deficiency as surface-placed urea may be lost, reducing the N supply for soil organisms; aOM in F1 was mineralised instead. In SD + U, however, the maintenance of total SOC level may be mainly attributed to the lowest loss of mineral-associated carbon (F3). Well-decomposed compost, and single urea application in tilled as well as in no-till plots did not lead to an accumulation of POC but to a more stabilised organic carbon. It may be argued that the quantity of carbon input applied through the different organic resources may affect SOC dynamics. However, in high nitrogen-depleted soils such as those of semi-arid West Africa, the quality of organic resource applied affects more SOC dynamics than its quantity. Indeed, to meet their N needs, soil micro-organisms will "burn" very high amount of low quality organic material (high C:N ratio) for the same equivalent N in high quality organic material (low C:N ratio). In these conditions, the SOM "pays" for the cost of crop N nutrition (Manu et al., 1991). This explains why in 2000, application of 2343 kg ha^{-1} of carbon through maize straw in tilled plots yields 5.2 g kg^{-1} in SOC versus 5.5 g kg^{-1} in SOC after the application of only 415 kg ha^{-1} of carbon through compost. The same trend is observed in 2001 where application of 3361 kg ha^{-1}of carbon through maize straw induced lower SOC than application of 993 kg ha^{-1} of carbon through sheep dung (Table 5).

Chan et al. (2002) reported that the stability of micro-aggregates, particularly those <0.050 mm is related to SOC < 0.053 mm, whereas stability of the macro-aggregates, namely >2 mm, is determined by temporary forms of SOC such as roots and fungal hyphae and as such is more sensitive to management practices. It may be argued that the higher the magnitude of SOC dynamics, the lower the contribution of SOC to aggregate stability. Therefore, the magnitude in the dynamics of SOC in soil fractions (Fig. 3) suggests that soil aggregate stability is lower in S and C in tilled plots and C and S + U in no-till plots than in the other treatments. The magnitude of SOC dynamics may be an indicator of SOC quality.

5. Conclusion

The results showed that particulate organic matter was strongly affected by the management practices and confirms the above hypothesis that early change in soil carbon is reflected in the dynamics of particulate organic matter. Strong correlation between particulate organic nitrogen and crop nitrogen uptake in both tilled and no-till plots confirms that nitrogen in POM mostly affects crop performance. Tillage increased the contribution of particulate organic carbon to total organic carbon. The maintenance of soil carbon concentration with combined crop residues and urea is due to an enhanced incorporation of new organic matter in the coarse fraction and the reduction of soil carbon mineralisation from the fine fraction. The reduced decrease of soil carbon concentration with the combined easily decomposable organic matter and urea is due to a lower soil organic carbon loss in the fine fraction. Well-decomposed compost and single urea application in tilled as well as in no-till plots did not benefit the accumulation of total organic matter, which is mainly attributed to the loss in particulate organic carbon. The absence of organic and mineral inputs in the cropping systems increases the magnitude of soil carbon dynamics suggesting low stabilised soil aggregates. Nitrogen absorbed by the crop from the mineral-associated nitrogen was higher in tilled than in no-till plots. We conclude that combining recalcitrant organic amendments and nitrogen fertiliser is the best option in sustaining crop production with positive change in soil particulate organic matter and in reducing soil carbon decline in the more stabilised fraction responsible for soil structure maintenance in semi-arid West Africa.

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