No-Till Impact on Soil and Soil Organic Carbon Erosion under Crop Residue Scarcity in Africa

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Although no-till (NT) is now practiced in many countries of the world, for most smallholders, the crop residues are of such a value that they cannot be left on the soil surfaces to promote soil protection, thus potentially limiting NT benefits and adoption. In this study our main objective was to evaluate runoff, soil, and soil organic carbon (SOC) losses from traditional small-scale maize (*Zea mays*) field under conventional tillage (T) and NT, with crop residues cover of less than 10% during the rainy season, in South Africa. Six runoff plots of 22.5 m^2 (2.25 × 10 m) under NT and T since 2002 were considered. At each plot, soil bulk density (ρ_b) and SOC content of the 0–0.02 m layer were estimated at nine pits. Top-soil SOC stocks were 26% higher under NT than under T ($P = 0.001$). The NT reduced soil losses by 68% (96.8 *vs.* 301.5 g m^{-2} yr^{-1}, $P = 0.001$) and SOC losses by 52% (7.7 *vs.* 16.2 g C m^{-2} yr^{-1}, $P = 0.001$), and differences in runoff were not significant. Dissolved organic carbon accounted for about 10% of total SOC losses and showed significantly higher concentrations under T than NT (1.49 versus 0.86 mg C m^{-2} yr^{-1}). The less erosion in NT compared to T was explained by a greater occurrence under NT of indurated crusts, less prone to soil losses. These results showed the potential of NT even with low crop residue cover (<10%) to significantly reduce soil and SOC losses by water under small-scale agriculture.

Abbreviations: ρ_b, soil bulk density (Mg m^{-3}); DOC, dissolved organic carbon (mg L^{-1}); ER, enrichment ratio, the ratio between soil organic carbon content in the sediments to that in the bulk soils; NT, no tillage treatment; R, runoff amount (L); SC, sediment concentration (g L^{-1}); SOC, soil organic carbon; SOC_c, soil organic carbon concentration in the ≤2-mm soil material (g C kg^{-1}); SOC_s, soil organic carbon stock (kg C m^{-2}); SOC_l, soil organic carbon losses (kg C m^{-2}); T, conventional tillage treatment.

Soils are one of mankind's most important assets. We use soils mainly for agricultural and environmental issues such as food production and storage and filtering of water, but other important soil functions exist such as biological habitat, pool of genes, source of raw materials, and physical and cultural heritage.

Soil erosion is a natural phenomenon. But when the removal of the soil is faster than soil formation through bedrock weathering, soil erosion becomes a problem, often resulting in reduced ability of soils to perform their functions.

Serious soil erosion is now occurring in most of the world's major agricultural regions, and the problem is growing as more marginal land is brought into agricultural production (FAO, 2008). Because soil erosion is a major threat to the sustainability of soils and soil functions in the years to come, finding remediation to soil erosion is a key issue (FAO, 2008).

The NT systems are progressing both under large-scale and small-scale agriculture (Huggins and Reganold, 2008). No-till, where mechanical soil disturbance is minimized and permanent organic soil cover (consisting of a growing crop or mulch of crop residues) is maintained, is indeed seen to be a credible agricultural system for soil protection (Bolliger et al., 2006; Triplett and Warren, 2008). By keeping plant and crop residues on the soil surface longer than under T, NT has been demonstrated to prevent soil surface sealing (Bradford and Huang, 1994;

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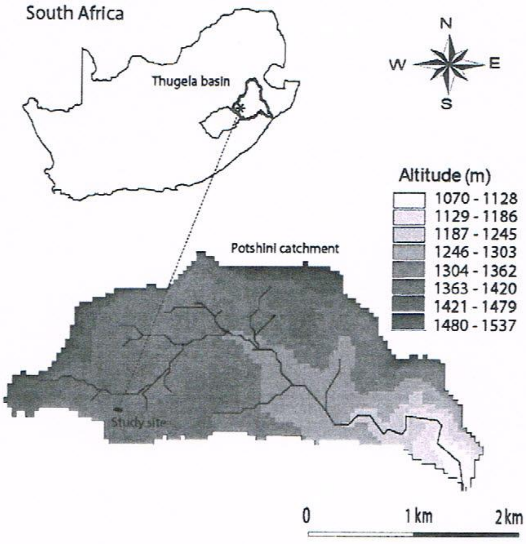

Fig. 1. Location of the study site within the Potshini catchment of the Thugela basin (South Africa).

Rao et al., 1998), prevent splash erosion (Bradford and Huang, 1994; Choudhary et al., 1997), and enhance soil porosity and soil infiltration through improved biological activity (Doran, 1980; Granatstein et al., 1987; Edwards et al., 1988, 1990; Meek et al., 1990; Pierce et al., 1994; Feng et al., 2003).

Furthermore, NT might be a suitable agricultural practice to mitigate the increasing atmospheric CO_2 concentration and associated global warming. Tillage and splash erosion break down soil aggregates, thus making SOC more accessible to the living decomposers, therefore T is expected to reduce SOC stock while NT enhances it (Angers et al., 1997; Lal, 1997; Paustian et al., 2000; Bernoux et al., 2006) and reduces the emission of greenhouse gases, especially CO_2 (Six et al., 2002; Schuman et al., 2002). Studies on the impact of NT on SOC losses are numerous (Bernoux et al., 2006) and demonstrate the major impact of splash erosion that preferentially removes SOC from both temperate (VandenBygaart et al., 2002) and tropical (Chaplot et al., 2007) soils.

At present, NT is practiced on approximately 95 million ha worldwide, with the largest area in South America (approximately 47%), North America (approximately 40%), and Australia (approximately 9%) (FAO, 2008). Less than 5% of NT areas are located in the rest of the world, including Asia, Europe, and Africa. For most small-scale land holders, especially those in the lower-income groups, NT adoption that is strongly promoted by the international community (FAO, 2008), especially in Africa, is limited due to many constraints. Crop residues are of such a value that cannot be left on the soil surface to promote soil protection (Rodriguez et al., 2008). Moreover, other drawbacks of NT, such as the use of heavier herbicide applications, or even reporting on lack of significant gains in crop yields, labor, and water infiltration and erosion are being experienced (Giller et al., 2009).

In this study our main objective was to evaluate runoff, soil loss, and SOC loss under T and NT. The study was conducted on sloping land at a typical small-scale agriculture community in northwestern KwaZulu Natal. The climate in this area is subtropical and subhumid. The lowlands support rainfed production of maize cultivated by numerous small-scale farmers, while steep slopes and upland areas that have shallower soils are dedicated to cattle grazing. During the maize growing season and until harvest the cattle are grazed in communal upland rangelands, whereas after harvest the cattle have access to the crop residues on the cultivated fields. Since cattle constitute an important part of the Zulu smallholders' livelihood and because it is an important cultural asset, stocking rates are high, enhancing the need for fodder and crop residues.

MATERIALS AND METHODS

Study Area

Maize is a traditional crop in KwaZulu-Natal and NT systems are progressing both under large-scale and small-scale agriculture (Huggins and Reganold, 2008).

The study area is located within the sloping lands of the KwaZulu-Natal province of South Africa that are part of the Thugela basin (Fig. 1). It is an experimental trial located at the Potshini community, 10 km south of the town of Bergville (−28°48'36" E, 29°22'48" S). Following the classification of Köppen, the climate of the area is temperate with cold dry winters and rainy summers. It is the type of climate of the highlands inside the tropics of South Africa but also found in Central and South America (Mexico, central Argentina, Peru, Bolivia) and other African areas (Madagascar, Zambia, and Zimbabwe) where winters are noticeably dry and summers wet. The mean 30-yr annual precipitation at Bergville, 10 km North of our study site, is 684 mm; the potential evaporation is 1600 mm; and the mean annual temperature is 13°C (Schulze, 1997). In the landscape, steep slopes with shallow soils are used to graze cattle, whereas the lowland areas, characterized by gentle slopes (0–10%) and deep soils (>1.5 m), are used for rain-fed maize production. Maize is generally planted around mid-November. Farmers plow their lands and prepare the soil for sowing with draft oxen. Planting, weeding, and harvesting are done manually. Little to no fertilizer is used due to the limited access to funds. We selected a 600 m^2 (20 by 30 m) area of the lowlands with an average altitude above sea level of 1385 m and a mean slope gradient of 3%. Soils have been cultivated for several decades with the same farming system; NT was introduced on a portion of the area from 2002 as an experimental trial, and the remainder was plowed using oxen.

From visual examinations of soil samples collected at three soil profiles to a depth of 1.2 m across the area, soils are acidic Acrisols (IUSS Working Group, 1998), which are generally deep and homogeneous (average soil depth of 1.5 m). The A-horizon is a brown sandy loam (7.5YR4/4, 55 to 68% sand) and has a low clay percentage (17–19%) and a high content of fine sand (45–50%). It is 0.35-m thick, acidic (pH 4.9–5.2), and has a fine granular structure. It is characterized by a low cation exchange capacity [2–4 $cmol^{(+)}\ kg^{-1}$] and SOC content (from 9–12 g C kg^{-1}). A subsurface organomineral AB_W horizon (0.35–0.85 m) has similar texture but is lower in C and N and has a lower cation exchange capacity and base saturation. Beneath these horizons lie two clayey mineral subsurface (B_w) horizons which are reddish in color

(5YR4/6), have an apedal structure, and are significantly enriched with clay (211–224 g kg^{-1} for Bw1, and 297–326 g kg^{-1} for Bw2).

Installation of Runoff Plots and Land Management

A total of six 22.5-m^2 (2.25 by 10 m) runoff plots were laid out along a contour line, spaced 2 m apart. To avoid any discrepancy due to installation, these plots were installed in late 2006. The metal borders surrounding the microplots were inserted to a depth of 0.1 m. Three randomly selected plots have been installed in the area of the experimental trial being plowed by oxen and three other plots were set up in the NT area. For each plot, a collector, a 10 times splitter and an 80-liter tank were placed at the bottom end of each plot to evaluate and collect surface runoff. Following plot installation, two consecutive cycles of maize occurred. Since 2006, tillage has been performed manually using a hoe and without removing the plots' metal borders. For the present study, tillage to 0.2 m depth and planting occurred on 8 Jan. 2009. For both treatments, the first fertilizer applications (40 kg N ha^{-1}) occurred on 8 January and the second (40 kg N ha^{-1}) on 10 March. Herbicides (glyphosate at a rate of 4 L ha^{-1}) were applied twice on weeds, on 9 January and 10 March. Harvest occurred on 5 June 2009. The surroundings of plots were managed similarly.

Evaluation of Runoff, Soil, and Soil Organic Carbon Losses

After each rainfall event, the total runoff volume (R) from each replicate plot was collected in the 80-liter collector and was measured with a graduated tube. The precision was of 2 to 5 mL for total runoff volumes between 10 and 2000 mL, and ±10 mL for larger runoff volumes.

For all erosive events, the total runoff amount was stirred before taking a 800-mL sample aliquot that was afterward oven-dried at 70°C to estimate sediment concentration (SC) in the runoff. The total sediment losses from a plot was then estimated as the product of R and SC. Total C and N were estimated using a LECO CNS-2000 Dumas dry matter combustion analyzer (LECO Corp., St. Joseph, MI).

For five events for which an operator was present at the time of the rain, the contents of the collection tank were stirred and an aliquot of 100 mL was collected for the estimation of dissolved organic carbon (DOC). Following Johnson et al. (1993), samples were preserved by adding HCl (1/10) to pH < 2 and refrigerated at 4°C until analysis (24 h at the most).

Samples are stored at 4°C in glass bottles with HgCl2 as a preservative and analyzed by a high precision coulometric titration using a UIC Coulometrics CO_2 analyzer (UIC, Joliet, IL). The precision of this instrument is 0.05% (1 μM) (Johnson et al., 1993).

Dissolved organic carbon was determined at a maximum delay of 24 h after sampling using a Shimadzu (Kyoto, Japan) TOC-5000 analyzer with ASI-5000 autosampler and Balston 78-30 high purity total organic C gas generator (Parker Hannifin Corp., Haverhill, MA). Excess water was then decanted and sediments dried at 105°C for 24 h. The sediments were weighed to determine SC in runoff and ultimately to compute sediment losses.

Evaluation of Soil Surface Features

The proportions of the soil surface covered by crop residues and soil surface crusts were considered for this study. The proportion of the different surface features was estimated visually by expert judgment using a 1-m^2 grid with 100-cm^2 cells (Auzet et al., 2004). The proportion of the soil surface with crusts was considered because of its recognized impact on runoff and water erosion (Casenave and Valentin, 1992). These authors indicated that surface crusts in semiarid and arid Africa significantly decrease soil infiltration by water. From the nine main types of crusts they identified only two types, namely the structural crust (a rough surface made of coalescing partially slaked aggregates) and the sedimentary crust a (made up of runoff deposition) which has a lower infiltration rate because of the laminated layers of different texture (Valentin and Bresson, 1992); these were observed at the study plots, and their extent quantified.

Observations were made on five dates: (i) 15 Dec. 2008 (before planting); (ii) 10 Jan. 2009 (immediately after tillage and planting); (iii) 14 Jan. 2009 (after the first rains); (iv) 5 June 2009 (immediately before harvesting), and (v) 10 June 2009 (immediately after harvesting). At each date, three observations were performed per plot, resulting in 90 observations.

Evaluation of Soil Organic Carbon Stocks

To better link SOC stocks with soil erosion which affect the surface soil profile only, soil samples were taken from the 0- to 0.02-m soil layer. Samples were collected on 13 Mar. 2009. Within each plot, 18 undisturbed samples were collected by coring at nine locations, the sampling being systematic: that is, a pit for every 2.5 m^2. The height of each coring was 0.02 m and the diameter was 0.04 m. Collected samples were stored at −4°C before analysis. The total organic C was determined using the LECO CNS analyzer. The determination of ρ_b was performed on a separate replicate by oven drying at 105°C for 24 h. The SOC stock of the 0- to 0.02-m soil layer was defined as follows:

$$\mathrm{SOC}_s = x_1 x_2 x_3 \left(1 - \frac{x_4}{100}\right) \times \mathrm{b} \qquad [1]$$

where SOC_s is the soil organic carbon stock (kg C m^{-2}) of the 0- to 0.02-m soil layer; x_1 is the SOC concentration in the ≤2-mm soil material (g C kg^{-1}); x_2 is the ρ_b (Mg m^{-3}); x_3 is the thickness of the soil layer (m); x_4 is the proportion of fragments of >2mm in percent; and b is a constant equal to 0.001.

Because changes in ρ_b between the T and NT treatments can result in errors in interpretation (Balesdent et al., 1990), these were further accounted for in the calculation of SOC storage. To prevent an overestimation of the mass of SOC in the soils of higher ρ_b, comparisons were made based on equivalent soil mass.

General Statistics

To compare the mean of the T and NT samples, a paired *t* test of the null hypothesis that the means of two populations are equal, was used in this study. Once a *t* value is determined, a *P* value can be found using a *t* distribution table. The 0.05 or 0.001 levels were used in this study to reject the null hypothesis in favor of the alternative hypothesis that suggests that the two treatments have different means.

RESULTS

Soil Organic Carbon Stocks

The average SOC_s for T was 13.19 ± 0.33 kg C m^{-3}, while that for NT was 17.70 ± 0.68 kg C m^{-3} (Table 1). These differences were

Table 1. General statistics of minimum (Min.), maximum (Max.), mean, variance (Var.), standard error (SE), coefficient of variation (CV) for soil organic carbon content (SOC_c); soil organic carbon stocks (SOC_s) expressed in equivalent soil mass basis; and soil bulk density (ρ_b) in soils (0- to 0.02-m soil layer) and sediments collected from the six erosion plots. Data computed from nine replicates per plot for soils and from five erosive events for sediments.†

	Soils						Sediments			
	SOC_c		ρ_b		SOC_s		SOC_c		SOC_s	
	T	NT	T	NT	T	NT	T	NT	T	NT
	–g C kg^{-1}–		–Mg m^{-3}–		–kg C m^{-3}–		–g C kg^{-1}–		–kg C m^{-3}–	
Min.	8.8	9.7	1.11	0.95	10.51	11.18	33.5	50.1	33.51	50.15
Max.	13.0	18.3	1.31	1.26	15.63	24.26	63.2	97.2	63.18	97.19
Mean	11.1	14.8	1.19	1.15	13.19	17.70	48.3	71.0	48.34	71.04
Var.	0.2	0.6	0.01	0.01	2.91	12.33	26.6	60.0	264	602
SE	0.09	0.15	0.02	0.02	0.33	0.68	0.99	1.49	3.13	4.72
CV	13	16	6	10	13	21	34	35	34	35

† NT, no-tillage; T, conventional tillage.

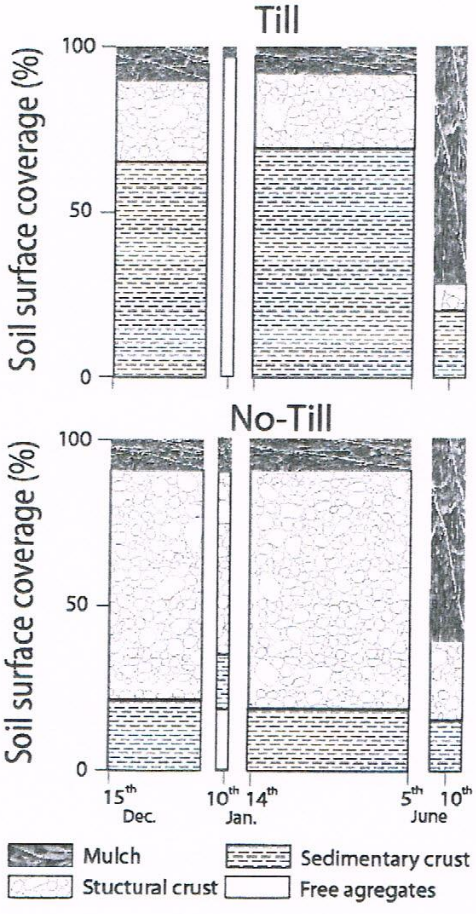

Fig. 2. Temporal variations of the average proportion of mulch, structural, and sedimentary (depositional) crust at the surface of plots under till and no-till. Three plot replicates and nine measurements per plot were considered.

Table 2. Paired *t* test statistics comparing till and no-till sample means for soil organic carbon content (SOC_c); soil organic carbon stocks (SOC_s) expressed in equivalent soil mass basis; and soil bulk density (ρ_b) for the 0- to 0.02-m layer of soils and sediments collected from the six erosion plots. The enrichment ratio (ER) is the ratio between SOC_c in the sediments to that in the contributing soils. Data computed from nine replicates per plot for soils and from five erosive events for sediments.

	Soils			Sediments	
	SOC_c	ρ_b	SOC_s	SOC_c	ER
t value	–7.06	2.45	–6.55	–1.92	1.24
df	26	26	26	14	14
P	0.000***	0.021*	0.000***	0.08	0.511

* Significant differences at $P < 0.05$.

*** Significant differences at $P < 0.001$.

significant at the $P < 0.001$ level (Table 2). The SOC_s estimated at nine locations per runoff plot ranged between 10.51 and 15.63 kg C m^{-3} for T, and from 11.18 to 24.26 kg C m^{-3} for NT. The greater heterogeneity in SOC_s for NT compared with T was confirmed by a variance of 12.33 kg C m^{-3} for NT versus 2.91 kg C m^{-3} only for T.

The mean soil organic carbon content (SOC_c) of the 0- to 0.02-m layer was 11.1 g C kg^{-1} under T (with standard error of 0.09 g C kg^{-1}) compared with 14.8 g C kg^{-1} under NT (with standard error of 0.15 g C kg^{-1}) (Table 1), and these differences were significant at $P < 0.001$ (Table 2). Mean ρ_b was 1.15 Mg m^{-3}, with SE of 0.02 Mg m^{-3} under NT and 1.19 Mg m^{-3} with SE of 0.02 Mg m^{-3} (Table 1) under T, and the differences were significant (Table 2).

Rainfall and Soil Surface Conditions

The cumulative rainfall from 1 Sept. 2008 to 30 June 2009 was 864 mm, of which 351 mm occurred after planting. Rains occurred in 30 events ranging between 0.6 and 80 mm, with maximum 6-min rainfall intensity ranging from 0.1 to 36 mm h^{-1}. Five main rainfall events having a cumulative rainfall over 20 mm each occurred during the season. The first one with an accumulative rain of 21 mm and a 6-min rainfall intensity of 3 mm h^{-1} took place on the day of planting (10 January). The largest event followed on 28 January (80 mm of rain); however, the rainfall intensity during this event was fairly low (maximum of 3 mm h^{-1}). Most of the rainfall occurred between end of January and 15 February. On 30 January and 10 and 15 February, events with a 24 mm h^{-1} intensity occurred.

During the study period, the soil surface coverage under NT was dominated by structural crusts, whereas the coverage under T exhibited a higher proportion of sedimentary and runoff depositional crusts (Fig. 2). On 15 Dec. 2008, T plots were characterized by a predominance of sedimentary crust (66% of the total soil surface) followed by structural crust (27%) and mulch (6%) (Fig. 2). On the same date, 67% of the soil surface of NT plots was covered with structural crusts, while the proportion of sedimentary and runoff depositional crusts was 23%, and that of mulch was 10% (Fig. 2). The NT exhibited similar proportions during the rainy season, until harvest where the proportion of mulch increased to 69%. Soil tillage that occurred on 10th of

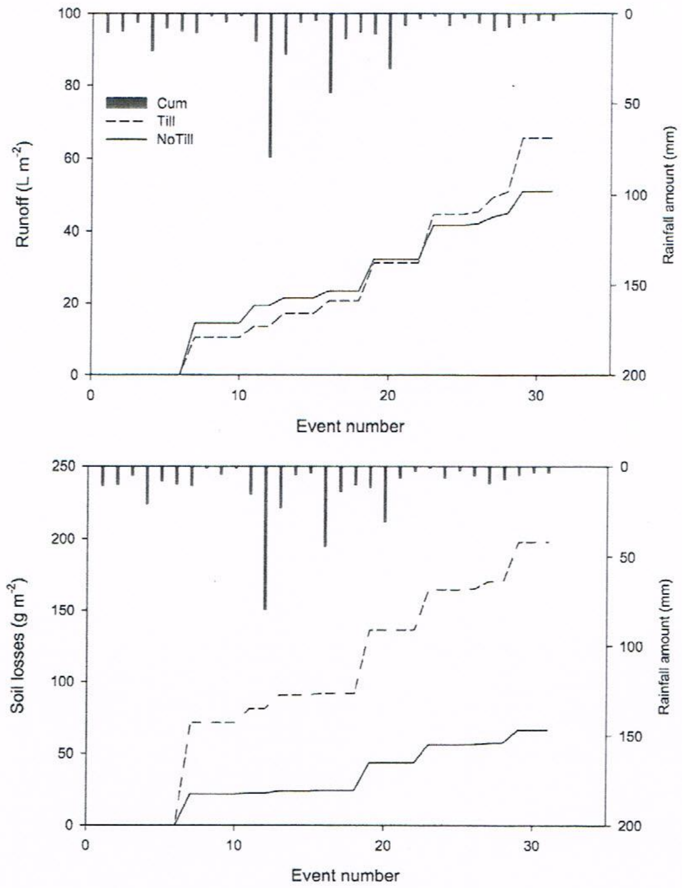

Fig. 3. Mean cumulative runoff and soil losses over the 2008–2009 rainy season for till and no-till maize. Data computed from three plot replicates per treatment. Rainfall amounts of the 31 rainfall events of the study period.

January destroyed the surface crusts and entirely covered the soil surface with free soil aggregates. Four days later the proportion of crust increased dramatically to 22% for structural crusts and 67% for sedimentary and depositional crusts, and no free aggregates remained at the soil surface. Just after harvest, performed on the fifth of June, 71% of the soil was covered by maize mulch, but this was being actively depleted by cows. The NT plots that exhibited a proportion of about 10% of free aggregates at planting were characterized by a proportion of structural crust of about 70% that remained constant to the end of the rainy season.

Runoff, Soil, and Soil Organic Carbon Losses

No runoff occurred for the three rainfall events (cumulative amount of 26.2 mm) that occurred between 2 and 10 January. Runoff started on the day of planting (10 January). The average runoff during the three following events (with a cumulative rainfall of 39 mm and maximum rainfall intensity of 24 mm h^{-1}) was 25% in NT and 36% in T (Fig. 3). Thereafter, the cumulative runoff curve of both T and NT exhibited a less-steep increase up to 15 February (corresponding to Event 19 of Fig. 3, with a rainfall amount of about 30 mm), even for the largest event of the season with a total rainfall of 80 mm and a maximum 6-min rainfall intensity of 3 mm h^{-1}. Later in the year, sharp increases of the cumulative runoff only occurred at rainfall events with high rainfall intensity (~25 mm h^{-1}). Finally, R tended to be lower in T than in NT during the half of the rainy season, while the reverse occurred afterward (Fig. 3), but these differences were not statistically significant (Table 4).

The median runoff volume was 5.9 L per event in NT and 9.3 L in T (Table 3). On a yearly basis however, the differences for runoff between T and NT were not significant (Table 4).

Mean SC in runoff was 0.9 g L^{-1} for NT and 2.2 g L^{-1} for T. A maximum of 8.2 g L^{-1} occurred on 10 January on a tilled plot (Table 3). The distribution of SC data was skewed and more peaked than the normal distribution. Mean SC was 0.9 g L^{-1} for T and 2.2 g L^{-1} for NT, and these differences were statistically significant as was shown in Table 4.

Soil losses were 3.1 times greater under T (301.5 g m^{-2}) than under NT (96.8 g m^{-2}), which was statistically significant (Table 4). The average SOC$_c$ in sediments from both treatments

Table 3. General statistics (Min., minimum; Max., maximum; Avg., average; Median; Var., variance; SD, standard deviation; CV, coefficient of variation; Skwe., Skweness; Kurt., kurtosis; Q1, Quartile 1; Q3, Quartile 3) for runoff (R), sediment concentration (SC), soil loss (SL), dissolved organic carbon (DOC), and soil organic carbon content (SOC_c) for till and no-till treatments. Data computed from the three plot replicates of 22.5 m^2 per treatment and the 10 erosive events of the 2008–2009 rainy season.

	R	SC	SL	DOC	SOC_c
	L	g L^{-1}	g m^{-2}	mg C L^{-1}	g C kg^{-1}
			No-till		
Min.	0.0	0.0	0.0	4.7	52.0
Max.	42.3	3.2	3.1	6.6	110.0
Avg.	11.5	0.9	0.7	5.9	86.0
Median	5.9	0.6	0.1	6.5	96.0
Var.	123.6	0.7	0.8	0.8	63.2
SD	11.1	0.9	0.9	0.9	25.1
CV	96.7	92.0	134.3	15.2	292.3
Skwe.	1.0	1.0	1.2	–0.7	–0.6
Kurt.	0.4	0.5	0.4	–1.6	–1.6
Q1	2.8	0.2	0.0	4.7	52.0
Q3	20.3	1.4	1.3	6.6	110.0
			Till		
Min	0.0	0.0	0.0	7.7	58.0
Max	36.6	8.2	10.8	8.3	72.2
Avg.	14.7	2.2	2.0	8.0	65.1
Median	9.3	1.9	1.0	8.0	65.1
Var.	130.8	3.9	6.2	0.1	3.5
SD	11.4	2.0	2.5	0.3	5.9
CV	77.6	89.8	126.2	3.4	9.1
Skwe.	0.6	1.4	1.9	0.0	0.0
Kurt.	–1.2	1.9	4.4	–1.6	–1.6
Q1	6.8	0.6	0.1	7.7	110.0
Q3	23.8	2.8	2.9	8.3	182.2

was 75.55 g C kg^{-1} (Table 3). This was much higher than the average SOC_c of the soil surface layer of 12.9 g C kg^{-1} and corresponded to an enrichment factor from the bulk soil of 5.9.

The SOC_c differences between the two treatments (Fig. 4A) were significant as well (Table 4). Greater losses of DOC occurred under T (average of 8.0 mg C L^{-1} versus 5.9 mg C L^{-1} for NT) and this was highly significant (Table 4). Overall, DOC losses represent on average 10.9% of total soil organic carbon losses (SOC_l) by water erosion.

The computed SOC_l were 16.2 g C m^{-2} yr^{-1} for T, which was significantly different from 7.7 g C m^{-2} yr^{-1} for NT (Table 4), and corresponded to 6.0 and 2.4% of the total SOC stock in the 0- to 0.02-m soil layer, respectively.

Table 4. Paired *t* test statistics comparing till and no-till sample means for runoff (R), sediment concentration (SC), soil losses (SL), soil organic carbon concentration (SOC_c), dissolved organic carbon (DOC), and soil organic carbon losses (SOC_l) from the runoff plots. Data computed from the six plot replicates of 22.5 m^2 and the 10 erosive events of the 2008–2009 rainy season.

	R	SC	SL	SOC_c	DOC	SOC_l
t value	2	4.34	3.98	–4.22	16.84	4.16
d.f.	29	29	29	29	29	29
P	0.053	0.000***	0.000***	0.000***	0.000***	0.000***

* Significant differences at $P < 0.05$.

*** Significant differences at $P < 0.001$.

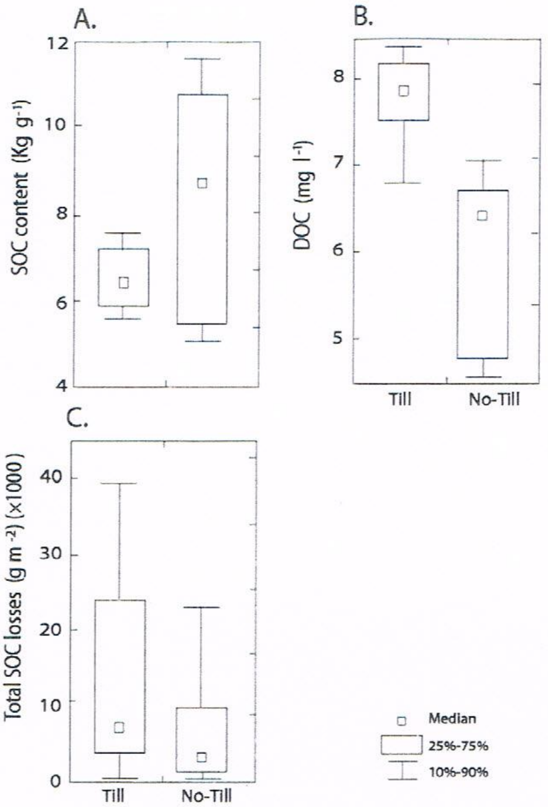

Fig. 4. Box-plots for soil organic carbon content (SOC) in sediments; dissolved soil organic carbon (DOC) in runoff; and total SOC losses exported from the plots. Data computed from the six plot replicates and for five of the 10 erosive events.

DISCUSSION

Differences in Soil Organic Carbon Stocks between Till and No-Till

In this study, SOC content and stocks in the 0- to 0.02-m layer were 33 and 26% higher under NT than under T, which was highly significant. This is concordant with available studies on the subject (Rasmussen and Collins, 1991; Reeves, 1997; Lal, 1997; Paustian et al., 2000; Potter et al., 2007). It has been reported that NT in North America can store an additional 1.3 t C ha^{-1} compared with T (Reicosky et al., 1995; Cambardella and Elliott, 1992; Lindstrom et al., 1998). This amount can be as high as 1.7 t C ha^{-1} yr^{-1} per year in Brazil (Bernoux et al., 2006).

In the present study, the fact that a very limited amount of crop residue left on the soil surface is shown not to be a limitation for SOC sequestration. In a similar study where NT was operated with no crop residues, Potter et al. (2007) showed enhanced SOC levels under NT with all surface residues removed when compared with plowing with the incorporation of all residues. This observation may have resulted from the greater physical

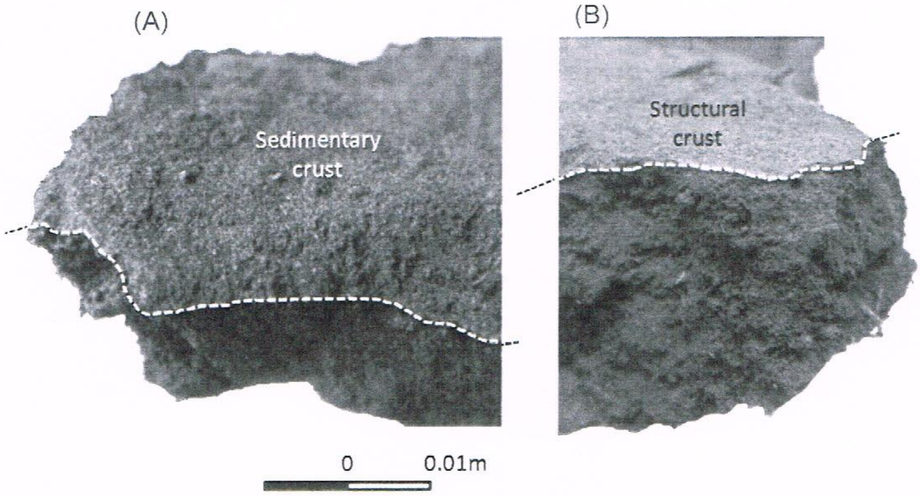

Fig. 5. Soil surface characteristics of a (A) sedimentary and a (B) structural crust at the study site. The dotted lines shown the limit between the soil surface and the soil matrix.

protection of SOC by large aggregates (Six et al., 1999; Chenu et al., 2000; Denef et al., 2001). Furthermore, SOC accumulation due to NT generally occurs within the top few centimeters of the soil surface (Eghball et al., 1994), where significantly greater C and N concentrations in particulate and mineral-associated pools are generally found compared with T (Dell et al., 2008).

The topsoil of maize plots was enriched in SOC after 6 yr of NT by 26% on average. This is relatively low compared with what could have been expected (Schlesinger, 2000).

Several hypotheses may be proposed to explain this. The first hypothesis is that because the SOC levels for NT are generally greatest at the surface and least in the subsoil (Eghball et al., 1994; Dell et al., 2008), increases in SOC content in the surface layers are sometimes compensated by a greater soil compaction and/or lower SOC stocks at depth (Angers et al., 1997; McCarty et al., 1998; Campbell et al., 1999; Six et al., 1999; Schlesinger, 2000). The second hypothesis is that the success of NT for SOC sequestration varies with soil texture and climate, the highest accumulation rates generally occurring in temperate conditions and sandy soils compared with tropical and clayey soils (Needelman et al., 1999; Schlesinger, 2000; Potter et al., 2007). Potter et al. (2007) conducted a multiyear study in Mexico under a wide range of climatic conditions, and showed that the impact of residues with NT on soil SOC stocks may differ between climates, with warmer climates inducing a complete decomposition of the residues left on the soil surface without improving SOC content. It is possible that this hypothesis may explain the relatively low SOC enrichment of the topsoil layer observed at the study site. A third hypothesis is related to the fact that conversion of T to NT generally leads initially to a lower SOC content and a subsequent SOC increase after 10 yr of NT (Riezebos and Loerts, 1998). According to Williams et al. (2009), a sequestration peak can be expected after 5 to 10 yr, with SOC reaching a new equilibrium in 15 to 20 yr. Confirmation or rejection of this last hypothesis would require longer-term SOC evaluations.

Impact of No-Till on Runoff

Under the conditions of the study, NT did not decrease runoff ($P = 0.05$). This result was surprising, considering that soil infiltration pathways are more likely to be preserved by the absence of tillage. Lindstrom et al. (1998) in Minnesota using rainfall simulation (70 mm h^{-1}) showed that runoff coefficient was 24 to 66% for T and approximately 3% for NT, which corresponded to a 93% difference. This was an upper-bound value of runoff decrease obtained in such studies. This result was consistent with those reported by Zheng et al. (2004), who reviewed different experiments performed in the United States and stated that the median decrease was 10 to 40%, with only one experiment out of 12 having a runoff decrease of >90%.

In this study, differences in terms of soil crusting between T and NT plots (e.g., the predominance of sedimentary and depositional crusts under T and of structural crusts under NT) (Fig. 5), were expected to have induced differences in term of runoff. Soil surface conditions, which include features such as crusts, have been shown to play an important role in water infiltration into soils and runoff (Casenave and Valentin, 1992). In their evaluation of 87 runoff plots of 10 sites from Niger, Burkina Faso, Ivory Cost, Togo, and Cameroon, Casenave and Valentin (1992) found the infiltration rate of structural crusts with a limited number of microlayers ranged between 0 and 20 mm h^{-1}, and between 0 and 7 mm h^{-1} for sedimentary and depositional crusts. The reason for the lack of significant differences in terms of runoff might be due to similar infiltration characteristics of the two crust types at the study site and/or the presence, at both treatments, of areas of high infiltration by water as a result of faunal activity.

Significant difference for runoff between T and NT has not been previously reported, but only in the case of clayey soils

(Chichester and Richardson, 1992). Possible explanations for the lack of runoff differences between T and NT in our study are the limited amounts of residues returned that may have fostered biological activity in the NT plots.

Finally, the greater runoff under NT, compared with T, at the beginning of the rainy season and the vice versa toward the end of the season have not yet been reported in other studies. Runoff in NT was higher than that in T immediately following tillage in T in early season, probably because tillage disrupted the existing crusts and increased soil porosity and surface roughness in T, all of which potentially increased soil infiltration until a new crust was formed later in the season. However, this highly probable hypothesis needs to be further investigated and the significance of the observed trend further tested. Proposed investigations may answer questions such as: Is the observed trend seasonal or consistent over the year? Will it remain for a long time? How long does it take for the porosity resulting from tillage to clog up? What are the controlling factors of this porosity?

Impact of No-Till on Soil and Soil Organic Carbon Losses

No tillage has long been recognized to be an efficient way to reduce soil erosion (Wendt and Burwell, 1985; Choudhary et al., 1997; Zheng et al., 2004). Choudhary et al. (1997) observed that NT reduced soil erosion by a factor of 1.60 to 1.85. Zheng et al. (2004) in their review showed a reduction in soil erosion rates of between 30 and 99%. Two-thirds of the studies in their review reported a reduction proportion > 60%. For instance, Lindstrom et al. (1998) reported that the adoption of NT decreased soil erosion from 6.7–18.2 to 0.2 t $ha^{-1}yr^{-1}$. In small 0.6-ha-catchments in sloping land in Laos, Valentin et al. (2008) showed a sediment yield decreased from 5.7 to 0.7 t $ha^{-1}yr^{-1}$. In the present study, tillage reduced soil losses from 3.0 to 0.96 t $ha^{-1}yr^{-1}$. This shows a decrease of 68%, which falls in the upper range of rates reviewed above.

Literature presents that the overall reduction of soil erosion under NT is commonly attributed to the presence of crop residues on the soil surface that limit the impact of raindrops and favor infiltration (Bradford and Huang, 1994; Choudhary et al., 1997; Rao et al., 1998). However, in the present study, other explanations for the observed result may be found since residue provided partial protection during the process of being consumed by cattle in winter. Differences between T and NT might also be caused by a greater occurrence of structural crusts under NT, which were more resistant to detachment because of their greater compaction and greater hardness (Valentin and Bresson, 1992). Another explanation for the greater resistance of soils under NT might be the development of biological activity such as fungi and algae (Malam Issa et al., 1999, 2001). In the sloping lands of Laos and under clayey soil conditions, Chaplot et al. (2007) showed that water erosion decreased with increasing proportion of structural crusts (from 24.33 to 6.21 t ha^{-1} yr^{-1} for soil and from 1.46 to 0.31 t ha^{-1} yr^{-1} for SOC), not only due to the greater hardness of these, but also because of the greater occurrence of algae on the soil surface, which affords physical protection through binding and gluing. Malam Issa et al. (2001) also showed that cyanobacteria may significantly decrease the overall soil erosion because of the presence of algae filaments and residual organic matter below the superficial crusts, thus increasing soil aggregate resistance. However, no surface colonization by algae was found in our study (Fig. 5).

Another possible explanation of the greater resistance of crusts under NT might come from a greater microbial biomass C content such as those observed by Feng et al. (2003). This hypothesis needs to be investigated further.

Overall, both T and NT soils proved to be very sensitive to SOC losses. The SOC enrichment ratio (ER, the ratio of the concentration of SOC in the eroded materials to that in the contributing soils) was of about 6, and differences between the treatments were not significant. A number of investigators have reported ER for SOC >1, where the eroded material is enriched as compared with the bulk soil (Stoltenberg and White, 1953; Sharpley, 1980; Avnimelech and McHenry, 1984; Zobeck and Fryrear, 1986; Sutherland et al., 1996; Chaplot et al., 2007; Schiettecatte et al., 2008). Enrichment of SOC in sediments is possible since poorly decomposed soil organic materials that are light and noncohesive are the most physically mobile fractions of soils (Ghadiri and Rose, 1991). In the present study, ER was as high as 4.5, which corresponded to the highest levels reviewed by Avnimelech and McHenry (1984) for soils poor in SOC. The ER was slightly lower for T than NT, probably because ER tends to decrease as the intensity of soil erosion increases, since SOC is mainly concentrated within the surface soils of NT (Ritchie and McHenry, 1977). Our results showed that most of the SOC transported with sediments was in a particulate form (about 90 vs. 10% for dissolved organic carbon). The dissolved fraction, which is easily mineralizable (Gregorich et al., 2003; Cookson et al., 2005), was much lower than the 29 to 70% range observed by Jacinthe et al. (2002), and no significant differences existed between N and NT treatments. It was interesting to report greater DOC in T than in NT, even though organic C in soil and sediment of T was lower. Further investigations on organic matter types need to be performed.

CONCLUSIONS

The main conclusion of this study is that despite no additional soil surface coverage by the mulch, NT reduced soil losses by 68% and SOC losses by 52%, which was in both cases highly significant. Moreover, NT that limited the losses of the most labile fractions of the SOC, which are easy to decompose, might further limit greenhouse gas emissions from terrestrial ecosystems.

The decrease in the overall soil and SOC erosion with NT was not explained by differences in infiltration and runoff, but the development of structural crusts under NT previously shown to have greater resistance to detachment.

The NT with scarce residue appears a credible alternative to T. These results tend to show that residue scarcity should not be seen as a limiting factor for the implementation of NT since results in this study indicate significant benefits for soil protection and potential mitigation of greenhouse gas emissions. Under the conditions of the study, NT would be a more sustainable agricultural system than traditional tillage, but further research studies need to be performed in a longer term and under other climatic and soil conditions of Africa to draw more general and definitive conclusions.

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