SOIL ERODIBILITY CONTROL AND SOIL CARBON LOSSES UNDER SHORT TERM TREE FALLOWS IN WESTERN KENYA

Anja Boye[a] and Alain Albrecht[b]

[a] World Agroforestry Centre (ICRAF) P.O.Box 2389 Kisumu, Kenya
Email: anja@swiftkisumu.com,
[b] Institut de Recherche pour le Développement (IRD), BP 64501, 34394 Montpellier cedex 5, France, Email: albrecht@mpl.ird.fr

Résumé

Au Kenya, de nombreuses recherches ont eu lieu sur les jachères améliorée en ce qui concerne la production de nourriture et la fixation d'azote. Mais on a peu de données sur l'amélioration des propriétés physiques des sols, le ruissellement , l'érosion et les pertes de carbone . Cette étude vise donc 1/ l'impact à court terme d'une jachère améliorée sur le RU et l'infiltration durant le premier cycle de maïs, 2/ le contrôle de l'érosion et des pertes de C, 3/ l'intérêt du non labour sur le RU et l'érosion.

Le ruissellement et les pertes en terre ont été estimées sous pluies simulées (Type ORSTOM) sur deux sites du Kenya, un sol sableux et un sol argileux. Deux espèces ont été testées, *Crotalaria grahmiana et Tephrosia candida,* avec le maïs en continu (contrôle). Le ruissellement a été collecté sur 1m² et les échantillons prélevés toutes les minutes. Pour les deux sites , la jachère améliorée a réduit le RU (de 40%)et l'érosion (20%) par rapport au maïs. Dans cet essai , le RU et l'E n'ont pas été significativement différents pour le non travail et pour le labour conventionnel. Le % d'agrégats stables à l'eau etles pertes de carbone par érosionont été influencés par la texture du sol et le traitement. Les pertes en C.furent réduites de 30% (site 1) et 25% (site 2) et le stock de C total a été amélioré de 35% (site 1) et 10 à 16% (site 2). A court terme , la jachère améliorée peut être utilisée pour réduire le ruissellement et l'érosion, y compris les pertes en carbone.

Mots-clés : Kenya, ruissellement, érosion, pertes de carbone, stockage du carbone, simulations de pluies ORSTOM.

Abstract

Much research has been carried out on improved fallows (by planting legume trees and shrubs) in Western Kenya in relation to food production, nitrogen fixation, and phosphorous uptake. However, the role improved fallows play on the improvement of soil properties and control of runoff, erosion and associated carbon losses is less documented. The objectives of this study were thereby (i) to examine the effect of short-term improved fallows (18 months) on runoff, soil and carbon losses, and (ii) to examine the effect of no-tillage on runoff, soil and carbon losses. Runoff and soil loss were measured using a field rainfall simulator on two sites in Western Kenya, a sandy loam and a clay soil. Measurements were carried out at maize harvest, after a fallow phase or under continuous cultivation of maize intercropped with beans (control), on plots that had been either tilled or no-tilled after many years under conventional tillage. *Crotalaria grahamiana* and *Tephrosia candida* were tested as improved fallow species.

Improved fallows reduced runoff, soil and carbon losses under the subsequent maize crop for both sites. In average, runoff depth (mm) and rate (mm hr^{-1}) were reduced by 50% (sandy loam) to 70% (clay soil), and soil loss by 30% (sandy loam) to 80%(clay soil). Carbon losses were reduced by 20% (sandy loam; not significant) to 70% (clay soil). The proportion of topsoil C lost in sediments was much greater in the sandy loam than in the clay loam, but was not influenced by treatments. After one cropping season, no-tillage did not affect runoff or soil loss, but C losses on the sandy loam were much greater under no-tillage than under conventional tillage. The study showed that short-term improved fallows could successfully be used as a management tool to control runoff, soil erodibility and erosion-induced carbon losses, with greater impact on clay soil. Long-term experiments were however needed to further examine the effects of no-tillage.

Keywords : Improved fallow, runoff, soil loss, carbon losses, carbon stocks, no-tillage, Kenya

1. Introduction

Extensive research has been undertaken to understand the processes of soil erosion by water for different climates and soil types. While soil erosion is a natural process, anthropogenic influence through cultivation has exacerbated the rate of soil erosion. Accelerated soil erosion is the major land degradation process in Africa (Cooper et al., 1996). Soil erosion by water is a three-phase process: (i) detachment of soil particles by rain drops, (ii) transport of detached particles by runoff, and (iii) deposition of detached and transported particles. Cultivation makes the land more susceptible to runoff and soil erosion by removal of the permanent plant cover. Several studies have found close relationships between soil erodibility, soil organic carbon (SOC), and macro-aggregation (Le Bissonnais, 1996; Barthès et al., 2000; Barthès and Roose, 2002). SOC is widely acknowledged as one of the most important soil parameters to maintain good soil health (Doran et al., 1996). However, a considerable challenge exists to maintain adequate SOC levels for cultivated soils, especially in the tropics, where carbon losses through cultivation, decomposition and erosion often exceed carbon inputs. The main sources of SOC input in the tropics are returned biomass (above and below ground biomass) and manures, which are often less than required to maintain adequate SOC levels (Nandwa, 2001). Agroforestry has shown to be a good management option to produce sufficient biomass and to maintain or increase SOC. In Western Kenya agroforestry practices such as planted fallows have been reported to produce 20 tons biomass per hectare in 8 to 18 months, which, when returned to the soil, increase SOC and soil macro-aggregation (Niang et al., 1998; IMPALA, 2001; IMPALA, 2002; Mutuo, 2004). Similar findings have been reported by Ingram (1990). The potential for soils to store carbon has been receiving much attention and several studies have shown the potential for agroforestry to sequester carbon above and below ground and in soil (Kursten and Burschel, 1993; Dixon, 1995; Ingram and Fernandes, 2001; Albrecht and Kandji, 2003). However, much less is known on the specific potential of planted improved fallows to sequester carbon and reduce erosion-induced C losses. Several studies have found selective detachment and transport of SOC and fine particles, resulting in depletion of SOC for *in situ* soil and enhanced SOC for depositional areas (Watung et al., 1996; Wan and El-Swaify, 1997; Jacinthe et al., 2002; Owens et al., 2002; Lal, 2003). Some studies report eroded C to be subjected to accelerated mineralization and thereby to contribute to CO_2 emissions from soils, whereas other studies suggest that deep burial of deposited sediments promotes C sequestration (Jacinthe et al., 2002; McCarty and Ritchie, 2002). Reducing runoff and soil erosion remains crucial for controlling erosion-induced C losses and more research is needed to fully understand the fate of eroded C. In Kenya, agroforestry is widely practiced to control runoff and soil erosion (Cooper et al., 1996) and Van Roode (2000) found contour strips and hedges in association with terracing to increase infiltration under the vegetative strips. However, focus has mainly been on slope hillsides and catchment scales and little attention has been given to the role agroforestry can play in controlling interrill erosion.

In recent years, minimum and/or no-tillage have been reported to reduce runoff through accumulation of SOC and enhanced soil aggregation (Arshad et al., 1999; Franzluebbers, 2002). These studies found negative correlation between enhanced SOC under NT and runoff. Several studies have found SOC to accumulate in the near surface soil layers for soils under no-tillage (NT) compared to conventionally tilled soils (Ingram and Fernandes, 2001). However, the accumulation of SOC under NT has generally been assessed years after conversion and these studies showed time to be a crucial factor. Few studies have focused on SOC accumulation under NT shortly after conversion and in association with agroforestry and planted fallows.

Thus, the aim of this study was to examine runoff and soil loss from long term cultivated Ferralic Arenosol and Ferralsol under simulated rainfall in the field for planted fallows (improved fallows). The following objectives were identified: (i) to examine the effect of short term improved fallows on runoff, soil and carbon losses, and (ii) to examine the effect of no-tillage on runoff, soil and carbon losses. The study was conducted at harvest of the first maize crop following fallowing.

2. Materials and methods

2.1 Site description

The study was conducted on farm at two locations in Western Kenya, Masai farm and Luero farm in July 2001. Masai farm (sandy loam) is located in Busia District (00°34.407'N, 034°11.554'E) at an altitude of 1290 m. Rainfall is bimodal with an annual mean of 1200 mm. Mean annual temperature is 21°C. The soil is a coarse Ferralic Arenosol (FAO) with 17% clay, 12% silt, and 71% sand. The slope gradient is 6%.

Luero farm (clay soil) is located in the highlands of Western Kenya in Vihiga District (00°06.818'N, 034°31.488'E) at an altitude of 1620 m. Rainfall is bimodal with a yearly mean of 1800 mm. Mean annual temperature is 22°C. The soil is a fine mixed nito-humic Ferralsol (FAO) with 40% clay, 24% silt, and 35% sand. The slope gradient is 7%. Table 1 lists the most important topsoil properties for the two sites.

2.2 Experimental design and management

For each farm the experiment was a randomized block design with three replicates, each plot measuring 18 m by 16 m. The experiment aimed at comparing continuous cultivation (CC) of maize (*Zea mays)* intercropped with beans (*Phaseolus vulgaris*), on the one hand, and intercropping of maize and beans preceded by a 18-month improved fallow of *Crotalaria grahamiana* (IF-Cg) or *Tephrosia candida* (IF-Tc), i.e. two legumes, on the other hand. The experiment was established in July 1999 (Figure 1). Improved fallows

Table 1. Topsoil characteristics (0-15 cm depth) at the beginning of the experiment for the two study sites, Masai and Luero (Kenya).

Soil type	Sand (%)	Silt (%)	Clay (%)	SOC (g kg^{-1})	N	C/N	pH_{H_2O}	Total P (g kg^{-1})	Exch. Ca (cmol$_c$ kg^{-1})	Exch. Mg
Sandy loam (Masai)	71	12	17	7.8	0.48	16.3	5.4	0.18	2.27	0.68
Clay (Luero)	35	25	40	16.9	1.40	12.1	5.3	0.47	3.94	1.23

Sand: 50-2000 μm; silt: 2-50 μm; clay: 0-2 μm; SOC: soil organic carbon; N: total nitrogen; P: phosphorus; exch.: exchangeable; Ca: calcium; Mg: magnesium

Table 2. Effect of cropping system on soil organic carbon (SOC), C/N ratio, bulk density and soil carbon stock for the sandy loam and the clay soil.

Soil type and treatment[a]	SOC (g C kg^{-1})		C/N	Bulk density (g cm^{-3})		SOC stock (g C m^{-2})	
	0-5 cm	5-10 cm	0-5 cm	0-5 cm	5-10 cm	0-10 cm	First 87.5 kg m^{-2}
Sandy loam, CC	8.6Aa[bc]	8.6Aa	13.9ABa	1.32Ca	1.37Ba	1157Aa	753Aa
Sandy loam, IF-Cg	11.3Aa	8.7Aa	13.5ABa	1.36Ca	1.49Cb	1408Aa	875Aa
Sandy loam, IF-Tc	11.2Aa	9.0Aa	14.5Ba	1.33Ca	1.56Cb	1466Aa	885Aa
Clay, CC	21.0Ba	19.6Ba	13.2Aa	1.08Bb	1.09Aa	2202Ba	1742Ba
Clay, IF-Cg	22.8Ba	20.0Ba	12.9Aa	1.04Bb	1.07Aa	2259Ba	1871Ba
Clay, IF-Tc	27.1Cb	21.6Ba	13.3Aa	0.90Aa	1.03Aa	2382Ba	2131Cb
LSD[d] for the sandy loam	3.7	2.8	1.1	0.16	0.12*	396	260
LSD for the clay	3.3**	2.4	0.8	0.06***	0.09	206	159***
LSD for site effect	3.1***	2.3***	1.2	0.11***	0.11***	284***	193***
Sandy loam, CT	10.4	9.3	14.1	1.30	1.45	1359	861
Sandy loam, NT	10.4	8.3	13.8	1.37	1.49	1328	814
Clay, CT	20.8	20.7	13.2	1.01	1.06	2142	1808
Clay, NT	26.4	20.2	13.1	1.00	1.06	2421	2021
LSD for the sandy loam	2.6	2.0	1.1	0.11	0.08	282	184
LSD for the clay	2.4***	1.8	0.6	0.04	0.09	204**	131**

[a]CC is continuous cultivation, IF-Cg improved fallow treatment with *Crotalaria grahamiana*, and IF-Tc improved fallow treatment with *Tephrosia candida*

[b] Means followed by the same upper case letter in the same column are not statistically different at p≤0.05

[c] Means followed by the same lower case letter for each site are not statistically different at p≤0.05

[d]LSD at p≤0.05

*, **, *** significant at 0.05, 0.01, and 0.001, respectively

were planted at the end of the cropping season in the former bean rows, which had been harvested in late June. The fallows were left to grow until February 2001, when they were slashed and the land prepared for the following maize crop. For the control plots, maize and beans were harvested every season (December 1999, July 2000, December 2000, August 2000, December 2001, and August 2001). During the first season (short rainy season 1999), all treatments were weeded twice by hand between September and October 1999. The following two seasons (long rainy season 2000 and short rainy season 2000) only the control plots (CC) were weeded (IMPALA 2001; IMPALA 2002). In February 2001, the fallows (IF-Cg and IF-Tc) were slashed by cutting the stem 10 cm above ground level.

After the 18-month fallow phase, maize and beans were planted, each plot being split into two. One part was tilled with a hand hoe, disturbing the soils to a depth of 10 cm (CT). The other part was left undisturbed (NT) except for planting operations (direct planting). For the CT plots the returned biomass was incorporated into the soil, whereas it was left on the soil surface for the NT plots. For the sandy loam, added residue biomass (from the improved fallow and the weeds) was 1.7 t ha^{-1} for IF-Cg and 2.1 t ha^{-1} for IF-Tc. For the clay soil, added biomass was 3.9 t ha^{-1} for IF-Cg and 7.8 t ha^{-1} for IF-Tc. The woody stems were removed from the system and used by the farmers. For the sandy loam, removed biomass amounted to 8.7 t ha^{-1} for IF-Cg and 10.6 t ha^{-1} for IF-Tc and for the clay soil to 19.7 t ha^{-1} for IF-Tc. Maize and fallows were planted with a spacing of 75 cm between rows and 25 cm within row. All plots were weeded twice between April and June 2001, and were harvested in August 2001.

2.3 Rainfall simulation

A field rainfall simulator (ORSTOM type) was used to produce artificial rainfall. The ORSTOM rainfall simulator simulates rainfall over 4 m^2 but measures runoff from a 1-m^2 plot. Rainfall is produced by a single nozzle, which sprinkles water in a downward direction. The nozzle is placed at a height of 4 m, enabling the raindrops to reach terminal velocity. For more detailed information on the ORSTOM rainfall simulator, see Asseline and Valentin (1978).

Two rainfall intensities were chosen, 50 and 90 mm hr^{-1}, to simulate low and high intensity rainstorms. Rainfall simulations were carried out at crop harvest (maize intercropped with beans) in August 2001. The simulation campaign consisted of three events. The objective was to simulate on dry, wet, and very wet soils. The first event was carried out on dry soils with medium rainfall intensity (50 mm hr^{-1}) and ran until steady runoff occurred (maximum 90 minutes). The following day two simulations were carried out on wet soils. The first event had an intensity of 50 mm hr^{-1} and the following one of 90 mm hr^{-1}. The duration was 30 minutes. A break of 15 minutes was held between the two rainfall simulations to allow runoff to cease. For each treatment and sub-treatment three replicates were carried out. Runoff was measured on a minute basis and sediment samples were collected for every two minutes until steady runoff had installed. At steady state, runoff sediment samples were collected every 5th minute. Before each simulation the loose soil cover was removed by hand. Thus, simulations were carried out on a bare soil surface where soil cover was less than 5%.

In this paper only data for the very wet run will be presented. This campaign has been chosen in order to discuss runoff, soil loss, and soil carbon losses for different land use systems and soil types. Majority of soil loss occurs at the on-set of the rainy season during high intensity storms. Thus, the very wet campaign simulated such scenarios and could thereby give an indication on soil carbon losses during natural rainfall.

2.4 Soil sampling and analyses

Soil samples were collected to determine bulk density, soil aggregate stability, soil carbon and nitrogen contents, and C/N ratio. Soil was sampled in June 2001 (before harvest of beans) at 0-5 and 5-10 cm depth using 98-cm^3 cores with three replicates for each plot. Water stable aggregates (WSA) were determined by wet sieving after shaking, with three replicates for each soil sample. Fifty g of air-dried soil was passed through a 2-mm sieve and shaken in 300 ml of water for one hour in a tumbler shaker at 50 revolutions per minute. The sample was then sieved through 212- and 20-μm sieves. For both soil types, WSA larger than 212 μm were expressed on a coarse sand-free basis (Albrecht et al., 1992; Feller et al., 1996). These samples were then bulked to comprise one sample per replicate (n=3). Soil resistance to penetration and shear stress were measured on-site using a penetrometer CL 700A (kg cm^{-2}) and a torvane CL 600 (kg cm^{-2}), respectively, produced by Gravquick, Esbjerg, Denmark. Soil resistance to penetration and shear stress were measured at the soil surface after each rainfall simulation next to the 1-m^2 plot. Each measurement was replicated six times.

Total carbon and nitrogen contents of soil and sediment samples were determined by the CNS Carlo Erba micro-analyser method. In the absence of carbonates, all carbon was considered organic. Soil carbon stocks were calculated for equivalent depth (0-10 cm) and for equivalent mass (this mass was 87.5 kg m^{-2} and corresponded to the smallest mass of the 0-10 cm soil layers under study, which was in the clay soil under IF-Tc and NT) as recommended by Ellert and Bettany (1995).

2.5 Data analysis

The data were statistically analyzed using ANOVA for a completely randomized block design with final runoff rate, runoff depth, sediment concentration, and soil loss as variables in the first analysis. In the second analysis, the variables were percentage water stable aggregates, soil carbon content, bulk density, C/N ratio, and soil resistance to penetration and shear stress. The third analysis had enrichment ratio, carbon losses, and soil C stocks as variables. Statistical significance was determined at the 95% confidence level with Tukey's test. Sediment carbon content was averaged for the three replicates, thus no statistical analyses could be done for this variable and for sediment C/N ratio.

A principal component analysis (PCA) was carried out with the ADE4 statistical package (Thioulouse et al., 1997), in order to identify the dominant factors explaining eroded carbon losses for the three land use systems and two sub-treatments. The variables were percentage water stable aggregates, soil resistance to penetration and shear, soil carbon content, and soil carbon losses.

3. Results

3.1 Soil carbon content, bulk density, C/N ratio, and carbon stocks (Table 2)

Soil carbon (C) content, bulk density (BD) and carbon stocks were influenced by site ($p \leq 0.001$). The clay soil had significantly higher soil C content for both depth increments regardless of treatment. Soil C content was more than double for the clay soil: 23.6 vs.

10.4 g C kg^{-1} at 0-5 cm depth and 20.5 vs. 8.8 g C kg^{-1} at 5-10 cm depth in average. Soil C content decreased with depth for both sites (15% in the sandy loam and 13% in the clay soil). Bulk density was lower in the clay soil than in the sandy loam for both depth increments, 25% at 0-5 cm depth (1.01 vs. 1.33) and 38% at 5-10 cm depth (1.06 vs. 1.47). Bulk density increased with depth for both sites (10% and 5% for the sandy loam and clay soil, respectively). C/N ratio (0-5 cm depth) ranged from 13.2 to 14.5 and was not affected by soil type in general. However C/N was significantly higher (ca. 10%) in the sandy loam under IF-Tc than in the clay soil under CC and IF. Carbon stocks were significantly greater in the clay soil than in the sandy loam: 70% greater considering the 0-10 cm depth layer (2280 vs. 1340 g C m^{-2}), and 130% greater considering an equivalent soil mass (87.5 kg m^{-2}, which was the smallest mass of the 0-10 cm soil layers under study) (1920 vs. 840 g C m^{-2}).

Treatment (CC vs. IF) and tillage practice (CT vs. NT) had greater effect on soil properties in the clay soil than in the sandy loam. For the former, soil C content at 0-5 cm depth increased by 29% under IF-Tc (27 vs. 21 g C kg^{-1}, $p \leq 0.01$), and was intermediate under IF-Cg (not significant). In contrast, soil C content did not differ significantly between treatments at 5-10 cm depth (it ranged from 19.6 to 21.6 g C kg^{-1}). In the sandy loam, IF did not significantly increase soil C content at 0-5 cm and 5-10 cm depths (it ranged from 8.6 to 11.3 g C kg^{-1}). NT increased soil C content in the clay soil by 27% at 0-5 cm depth, but tillage did not influence soil C content in the sandy loam and at 5-10 cm depth in the clay soil. In the clay soil, IF-Tc reduced BD at 0-5 cm depth by 17% (0.90 vs. 1.08 g cm^{-3}, $p \leq 0.001$), but no significant effect was seen under IF-Cg and at 5-10 cm depth. In the sandy loam, differences in BD were not significant at 0-5 cm depth (BD ranged from 1.32 to 1.36 g cm^{-3}), but increased under IF-Tc and IF-Cg at 5-10 cm depth (14 and 9%, respectively, $p \leq 0.02$). Tillage did not affect BD for the two sites for both depth increments. Soil C stocks at 0-10 cm depth did not differ significantly between treatments though they were greater under IF treatments than under CC (22 to 27% in the sandy loam, 3 to 8% in the clay soil). Considering C stocks at equivalent soil mass (the upper 87.5 kg m^{-2}) reduced differences between treatments in the sandy loam (16 to 18%) but increased differences between treatments in the clay soil (7 to 22%) so that difference between IF-Tc and CC was significant ($p \leq 0.001$). Both calculations (0-10 cm depth and 87.5 kg m^{-2}) indicated that C stock was 12-13% and significantly greater under NT than under CT in the clay soil ($p \leq 0.015$), but was not affected by tillage in the sandy loam. Large variations were seen in C stocks depending on the method of calculation. For the sandy loam, C stocks calculated for the 0-10 cm depth and equivalent soil mass differed considerably (1157 to 1466 vs. 753 to 885 g C m^{-2}), which was not the case for the clay soil (2202 to 2382 vs. 1742 to 2131 g C m^{-2}). The larger differences in C stocks for the sandy loam could be explained by larger BD. Indeed, soil mass for 0-10 cm depth was 1400 Mg for the sandy loam and 1050 Mg for the clay soil.

In short, soil C was greater and bulk density lower in the clay soil than in the sandy loam and at 0-5 than at 5-10 cm depth. As compared with CC and conventional tillage, soil C content generally increased in fallow treatments or under no-tillage at 0-5 cm depth in the clay soil, but neither at 5-10 cm depth nor in the sandy loam. The C/N ratio (0-5 cm depth) tended to be greater in the clay soil, but was not affected by treatment or tillage. Bulk density tended to decrease under fallow treatments in the clay soil but not in the sandy loam (it increased at 5-10 cm depth), and was not affected by tillage. C stocks were greater in the clay soil than in the sandy loam at 0-10 cm depth and at equivalent soil mass. Soil C stocks at 0-10 cm depth were not significantly affected by treatment, whereas C stocks at equivalent soil mass were greater after IF (IF-Tc) in the clay soil. Soil C stocks were not significantly affected by tillage.

3.2 Water stable aggregates and soil strength (Table 3)

Water stable aggregates (WSA) and soil strength were influenced by site ($p \leq 0.001$). Soil strength was measured *in situ* as soil resistance to penetration (RP) and soil resistance to shear (RS). WSA were greater in clay soil for both depth increments (350 to 420 vs. 50 to 60 g kg^{-1} at 0-5 cm depth and 350 to 410 vs. 40 to 50 g kg^{-1} at 5-10 cm depth). WSA generally decreased with depth, except for sandy loam IF-Cg and clay soil CC. Soil resistance to shear (RS) was 20 to 80% greater in the clay soil than in the sandy loam for all treatments (2.2 to 2.7 vs. 1.5 to 2.0 kg cm^{-2}), but the effect of soil type on RP was not clear.

Treatment and tillage influenced WSA and soil strength. At 0-5 cm depth, WSA increased significantly ($p \leq 0.003$) under both IF treatments in the clay soil (16% for IF-Cg and 21% for IF-Tc), but the effect of IF was not significant in the sandy loam. At 5-10 cm depth, WSA also increased significantly under both IF treatments in the clay soil (11% for IF-Cg and 15% for IF-Tc, only the latter being significant), but the increase was not significant in the sandy loam (though it reached 30 to 40%). No-tillage (NT) increased WSA by 12% ($p \leq 0.002$) in the clay soil at 0-5 cm depth, but tillage did not affect WSA at 5-10 cm depth or in the sandy loam. Soil strength was higher under CC than under IF treatments in the sandy loam: RP was 50 to 65% higher, and RS 18 to 32% higher. The relatively high soil strength under CC could be attributed to soil crusting. Under CC, the soil surface crusted within the first few minutes of the simulated rainfall event. There was no crusting on the clay soil. For the clay soil, IF-Tc increased RS by 13% but no increase was seen for IF-Cg. Conversely, IF-Cg significantly increased RP by 21%, but the effect of IF-Tc was not significant. Conflicting results were found for RP and RS in relation to tillage: NT increased RP and RS by 11 and 13 % in the sandy loam (significant for RS only) but decreased RP and RS by 16 and 11% in the clay soil, respectively.

In short, WSA increased under IF treatments and NT in the clay soil at 0-5 cm depth and under IF-Tc at 5-10 cm depth, but was not affected by treatment and tillage in the sandy loam. Resistance to penetration was not clearly affected by soil type. For the sandy loam it was 50 to 65% greater under CC than under IF treatments but was not affected by tillage, whereas for the clay soil it was not clearly affected by fallows but was 16% smaller under NT than under CT. Resistance to shear was 20 to 80% greater in the clay soil than in the sandy loam, and was 20-30% greater under CC than under IF treatments in the sandy loam, whereas fallow effect was not clear in the clay soil. As compared with CT, resistance to shear under NT was 13% greater in the sandy loam but 11% smaller in the clay soil.

3.3 Runoff, sediment concentration, and soil loss (Table 4)

Final runoff rate (FRR) and runoff depth (RD) were highly influenced by site ($p \leq 0.001$). Generally, FRR and RD were significantly lower on the clay soil than on the sandy loam when comparing treatment across sites: FRR was 36, 50 and 74% lower, and RD was 32, 78 and 60% smaller under CC, IF-Cg and IF-Tc in the clay soil than in the sandy loam,

Table 3. Effect of cropping system on water stable aggregates (WSA) and soil strength for the sandy loam and the clay soil.

Soil type and treatment[a]	WSA ($g\ kg^{-1}$) 0-5 cm	WSA ($g\ kg^{-1}$) 5-10 cm	Soil resistance to penetration ($kg\ cm^{-2}$) 0-10 cm	Soil resistance to shear ($kg\ cm^{-2}$) 0-2 cm
Sandy loam, CC	49.2Aa[bc]	38.6Aa	1.02Db	1.95Bb
Sandy loam, IF-Cg	42.2Aa	52.7Aa	0.62Aa	1.65Aa
Sandy loam, IF-Tc	60.1Aa	49.7Aa	0.68ABa	1.48Aa
Clay, CC	348.3Ba	353.2Ba	0.87CDab	2.38Ca
Clay, IF-Cg	403.1Cb	391.7Cab	1.05Db	2.23Ca
Clay, IF-Tc	421.1Cb	406.1Cb	0.82BCa	2.68Db
LSD[d] for the sandy loam	27.8	17.2	0.17**	0.25**
LSD for the clay	33.9**	45.6*	0.21*	0.18***
LSD for site effect	29.9***	29.6***	0.19***	0.21***
Sandy loam, CT	49.9	42.2	0.73	1.59
Sandy loam, NT	51.1	51.8	0.81	1.80
Clay, CT	368.0	374.4	0.99	2.57
Clay, NT	413.6	393.0	0.83	2.30
LSD for the sandy loam	21.3	12.5	0.13	0.18*
LSD for the clay	24.2**	33.8	0.15*	0.15**

[a]CC is continuous cultivation, IF-Cg improved fallow treatment with *Crotalaria grahamiana*, and IF-Tc improved fallow treatment with *Tephrosia candida*

[b] Means followed by the same upper case letter in the same column are not statistically different at $p \leq 0.05$

[c] Means followed by the same lower case letter for each site are not statistically different at $p \leq 0.05$

[d]LSD at $p \leq 0.05$

*, **, *** significant at 0.05, 0.01, and 0.001, respectively

Table 4. Effect of cropping system on runoff and soil loss for the sandy loam and the clay soil.

Soil type and treatment[a]	Final runoff rate[b] (mm hr^{-1})	Runoff depth[b] (mm)	Sediment concentration[b] (g l^{-1})	Soil loss[b] (g m^{-2})
Sandy loam, CC	70Cc[cd]	28Cc	0.96Aa	28.5Cb
Sandy loam, IF-Cg	24Aa	9Aa	0.88Aa	12.7Ba
Sandy loam, IF-Tc	50Bb	20Bb	0.94Aa	25.5Cb
Clay, CC	45Bb	19Bb	2.12Bb	13.1Bb
Clay, IF-Cg	12Aa	2Aa	0.72Aa	2.1Aa
Clay, IF-Tc	13Aa	8Aa	0.65Aa	4.2Aa
LSD[e] for the sandy loam	18***	8**	0.64	10.5**
LSD for the clay	18**	11*	0.90**	2.9***
LSD for site effect	15***	8***	0.71**	8.0***
Sandy loam, CT	51	21	0.74	20.3
Sandy loam, NT	45	17	1.11	24.1
Clay, CT	26	11	1.50	7.0
Clay, NT	20	9	0.82	5.9
LSD for the sandy loam	15	6	0.49	8.5
LSDfor the clay	13	8	0.70	2.3

[a]CC is continuous cultivation, IF-Cg improved fallow treatment with *Crotalaria grahamiana*, and IF-Tc improved fallow treatment with *Tephrosia candida*
[b]Final runoff rate, runoff depth, sediment concentration, and soil loss were measured over a 30 minute period
[c]Means followed by the same upper case letter in the same column are not statistically different at $p \leq 0.05$
[d]Means followed by the same lower case letter for each site are not statistically different at $p \leq 0.05$
[e]LSD at $p \leq 0.05$
*, **, *** significant at 0.05, 0.01, and 0.001, respectively

respectively (however differences in FRR and RD between sites were not significant for IF-Cg). Sediment concentration (SC) was less clearly influenced by site ($p \leq 0.004$): under CC it was twice higher on the clay soil than on the sandy loam, but under IF treatments it tended to be lower on the clay soil. Soil loss was highly affected by site ($p \leq 0.001$) and was two and six times greater on the sandy loam than on the clay soil for CC and IF treatments, respectively.

Treatment significantly affected FRR at both sites ($p \leq 0.001$ and $p \leq 0.004$ for the sandy loam and the clay soil, respectively), with greater reductions under IF treatments on the clay soil: as compared with CC, FRR was reduced by 71 to 73% for IF treatments on the clay soil, and by 66% for IF-Cg and 29% for IF-Tc on the sandy loam. A similar trend was seen for RD: IF-Cg and IF-Tc significantly reduced RD by 89 and 58% on the clay soil, and by 68 and 29% on the sandy loam, respectively. Tillage did not influence the runoff variables for the two sites. On the clay soil, IF significantly reduced SC ($p \leq 0.009$), which was three times lower than under CC (0.7 vs. 2.1 g l^{-1}). On the sandy loam, in contrast, the differences in SC between treatments were small (<10%) and not significant (SC ranged from 0.88 to 0.96 g l^{-1}). Additionally, SC was 45% smaller under NT than under CT on the clay soil, but 50% greater under NT than under CT on the sandy loam, however these differences were not significant. Treatment clearly influenced SL on the clay soil, where it was three and six times smaller in IF-Tc and IF-Cg than in CC, respectively (4 and 2 vs. 13 g m^{-2}, $p \leq 0.02$). On the sandy loam, SL was twice smaller in IF-Cg than in CC (13 vs. 29 g l^{-1}, $p \leq 0.02$), but did not differ significantly between IF-Tc and CC (26 vs. 29 g m^{-2}). Tillage did not influence SL for the two sites.

In short, runoff was smaller on the clay soil than on the sandy loam (30 to 80%) and for IF treatments than for CC (30 to 90%), but was not influenced by tillage. Sediment concentration was not clearly affected by soil type (for CC it was higher on the clay soil, for IF treatments it tended to be higher on the sandy loam). It was three times lower under IF treatments than under CC on the clay soil, but did not differ significantly between IF treatments and CC on the sandy loam. The influence of tillage on SC was neither clear nor significant. Soil loss was greater on the sandy loam than on the clay soil, and was smaller under IF treatments than under CC (on the clay soil especially), but was not significantly influenced by tillage.

3.4 Carbon content of sediments, enrichment ratio, and soil carbon losses (Table 5)

The effect of soil type on sediment C content was not clear (for CC and IF-Tc it was 63 and 94% higher on the sandy loam than on the clay soil, but for IF-Cg it was 67% lower on the sandy loam). C/N ratio of sediments was 26 to 46% higher on the sandy loam than on the clay soil across treatments (14 to 15 vs. 10 to 12). Carbon enrichment ratio of sediments (ER) and carbon losses were highly influenced by site ($p \leq 0.001$). ER was higher on the sandy loam (3.4 to 6.5) than on the clay soil (1.4 to 2.7), but the difference was significant for CC and IF-Tc only (6.1 vs. 1.5 and 6.5 vs. 1.4, respectively, $p \leq 0.01$). C losses were 3.4, 3.6, and 14 times greater on the sandy loam than on the clay soil for CC, IF-Cg and IF-Tc, respectively (however the difference was not significant for IF-Cg). They were maximum for IF-Tc on sandy loam (1.95 g C m^{-2}) and minimum for IF-Cg and IF-Tc on clay soil (0.12-0.14 g C m^{-2}).

On the sandy loam, C content of sediments was 40% lower for IF-Cg but 40% higher for IF-Tc than for CC (37 and 73 vs. 52 g kg^{-1}), whereas on the clay soil it was 95 and 20%

Table 5. Effect of cropping system on sediment carbon content, sediment C/N, ratio of sediment enrichment in carbon and carbon losses for the sandy loam and the clay soil.

Soil type and treatment[a]	Sediment C (g C kg^{-1})	Sediment C/N	Enrichment ratio	C losses (g C m^{-2})
Sandy loam, CC	52.1	14.3	6.1Cb[bc]	1.43Bab
Sandy loam, IF-Cg	37.4	15.1	3.4Ba	0.43Aa
Sandy loam, IF-Tc	73.3	13.9	6.5Cb	1.95Bb
Clay, CC	31.9	11.1	1.5Aa	0.42Ab
Clay, IF-Cg	62.3	12.0	2.7Bb	0.12Aa
Clay, IF-Tc	37.8	9.5	1.4Aa	0.14Aa
LSD[d] for the sandy loam	-	-	1.6**	1.14*
LSD for the clay	-	-	0.2***	0.10***
LSD for site effect	-	-	1.0***	0.77***
Sandy loam, CT	38.5	13.5	3.9	0.76
Sandy loam, NT	70.0	15.4	6.7	1.77
Clay, CT	37.2	10.9	1.8	0.24
Clay, NT	50.9	10.8	2.0	0.21
LSD for the sandy loam	-	-	1.1***	0.92*
LSD for the clay	-	-	0.1	0.08

[a]CC is continuous cultivation, IF-Cg improved fallow treatment with *Crotalaria grahamiana*, and IF-Tc improved fallow treatment with *Tephrosia candida*

[b] Means followed by the same upper case letter in the same column are not statistically different at $p \leq 0.05$

[c] Means followed by the same lower case letter for each site are not statistically different at $p \leq 0.05$

[d]LSD at $p \leq 0.05$

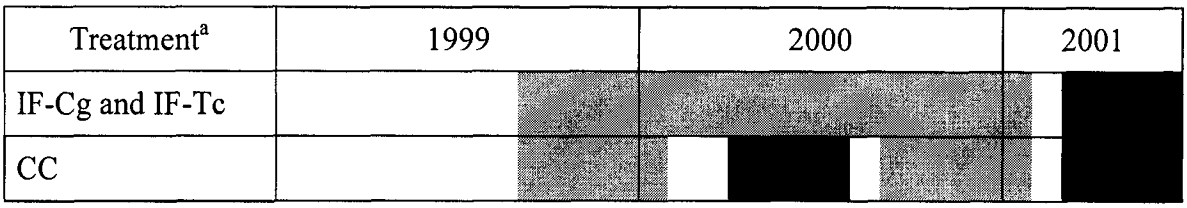
*, **, *** significant at 0.05, 0.01, and 0.001, respectively

higher for IF-Cg and IF-Tc than for CC, respectively (62 and 38 vs. 32 g C kg^{-1}). Additionally, sediment C content was 40% (clay) to 80% higher (sandy loam) under NT than under CT. Sediment C/N ratio was slightly lower for IF-Tc than for CC (3% on the sandy loam and 14% on the clay soil), but slightly higher for IF-Cg than for CC (6 and 8%, respectively). On the sandy loam, ER was similar in CC and IF-Tc but was twice lower in IF-Cg (3.4 vs. 6.1-6.5, $p \leq 0.01$). On the clay soil, it was also similar in CC and IF-Tc but was twice higher in IF-Cg (2.7 vs. 1.4-1.5, $p \leq 0.01$). Additionally, ER was 70% higher for NT than for CT on the sandy loam (6.7 vs. 3.9, $p \leq 0.001$), but was not significantly influenced by tillage on the clay soil (though 11% higher for NT). As compared with CC, both IF treatments reduced C losses by 70% on the clay soil (0.12-0.14 vs. 0.42 g C m^{-2}, $p \leq 0.001$). On the sandy loam, differences in C losses between CC and IF treatments were not significant though C losses were 70% greater for IF-Tc and 40% smaller for IF-Cg than for CC (1.95, 0.43 and 1.43 g C m^{-2}, respectively; C losses were 4.5 times greater for IF-Tc than for IF-Cg, $p \leq 0.05$). In contrast, C losses were not influenced by tillage on the clay soil, but were 2.3 times greater for NT than for CT on the sandy loam ($p \leq 0.035$).
C losses represented 0.03 to 0.13% of soil C stock at 0-10 cm depth in the sandy loam, but 0.01 to 0.02% only in the clay soil. Eroded C as a proportion of C stock (0-10 cm) was thus six to 20 times greater for the sandy loam than for the clay soil, whereas soil loss was only two to six times greater on the former than on the latter. The amount of eroded C as a proportion of soil C stock at 0-10 cm depth was not clearly influenced by treatment or tillage. However it was four times greater for CC than for IF-Cg on both soil types, and twice greater for NT than for CT on the sandy loam.
In short, sediment C content was not clearly affected by site (it was greater on the sandy loam for two out the three treatments) but was generally greater for IF treatments than for CC (except for IF-Cg on the sandy loam). Sediment C/N ratio was greater on the sandy loam than on the clay soil, with IF-Cg > CC > IF-Tc. Carbon enrichment ratio of the sediments was greater on the sandy loam than on the clay soil, was similar for CC and IF-Tc, and was twice greater for NT than for CT on the sandy loam. C losses were greater on the sandy loam, generally smaller for fallow treatments (except IF-Tc on the sandy loam), and were twice greater for NT on the sandy loam. The proportion of soil C stock lost with sediments was much greater for the sandy loam than for the clay, but was not clearly affected by fallow or tillage.

3.5 Principal component analysis (Figure 2)

The eigen values of the principal component analysis (PCA) showed that the first factor accounted for 59% of the total inertia. On the correlation circle this factor was represented by the horizontal axis (F1), which opposed water stable aggregates (WSA), soil C content, soil resistance to shear (RS), on the one hand, and C losses, on the other hand (Figure 2a). The second factor accounted for 23% of the total variation (F2), and was mainly explained by soil resistance to penetration (RP). The first two axes accounted for 82% of the inertia.
The factorial map of treatments (Figure 2b) showed the effects of soil type and treatment on soil C losses. The points, which represented the plots, clustered into two main groups: the first group, on the right part of the map, included the plots located on sandy loam, whereas the second group, on the left part of the map, included the plots on clay soil.

Figure 1. Cropping sequences for the cropping systems under study (black represents the cropping phase and grey the fallow period; for CC the fallow is a natural fallow).



[a]CC is continuous cultivation, IF-Cg improved fallow treatment with *Crotalaria grahamiana*, and IF-Tc improved fallow treatment with *Tephrosia candida*

Figure 2. Results from principal component analysis (PCA) on soil carbon losses

Figure 2. F1-F2 correlation circle of variables (RP and RS are soil resistance to penetration and shear, respectively, and WSA water stable aggregates).

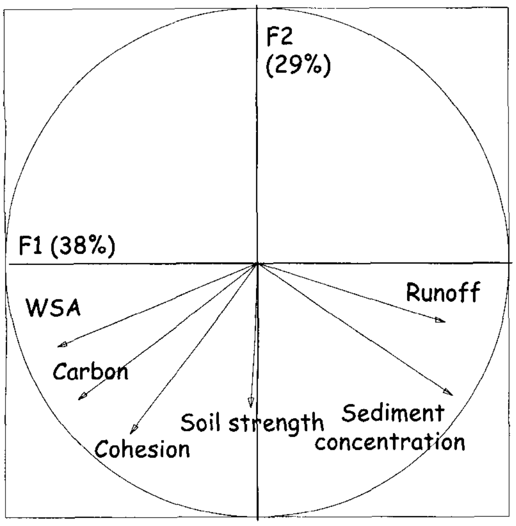


Fig 2b

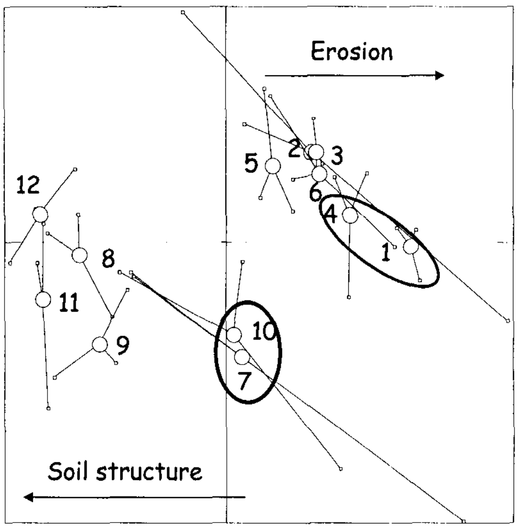


Fig 2c

No. 1-6 Site 1: (1) CM-T (2) CG-T (3) TC-T (4) CM-NT (5) CG-NT (6) TC-NT
No. 7-12 Site 2: (7) CM-T (8) CG-T (9) TC-T (10) CM-NT (11) CG-NT (12) TC-NT

Thus the projection on the F1 axis led to an opposition between the clay soil, which had greater soil C content, WSA and RS but smaller C losses, and the sandy loam, where soil C content, WSA and RS were smaller and C losses greater. This projection also showed that on clay soil, the plots representing IF-Tc CT, IF-Tc NT and IF-Cg NT (No 9, 10 and 12), on the left, had smaller C losses than CC CT, CC NT and IF-Cg CT (No 7, 8 and 11). This was interpreted as resulting from greater WSA after fallowing, which however was not achieved for IF-Cg CT (No 11).
The projection on the F2 axis allowed a distinction among plots on sandy loam between those under CC, toward the top of the map and having greater RP, and those under IF treatments, which had smaller RP (this distinction was not possible on clay soil). The projection on the F2 axis also separated the plots according to tillage: on the sandy loam, plots under NT had greater RP than their counterparts (same treatment) under CT; on the clay soil, on the contrary, plots under NT had smaller RP than their counterparts under CT (except for IF-Cg, No 11 and 12). Additionally, IF-Tc NT on clay soil (No 10) was at the bottom of the map, clearly below the other IF plots (No 9, 11 and 12), and this was related with a lesser RP on the formers than on the latters.
In short, the PCA analysis indicated that C losses were negatively related with soil C content and WSA, which were lower (i) on sandy loam than on clay soil, and (ii) among plots on clay soil, under continuous cultivation than after fallow (except on IF-Cg CT). On the clay soil, increases in soil C content and WSA through fallowing thus resulted in C loss reduction. In contrast, C losses on sandy loam could not be easily explained using the PCA, as the plots mainly ranged according to RP, which was perpendicular to C losses.

4. Discussion

4.1 Impact of improved fallows on runoff

Results on runoff depth and runoff rate indicated that fallowing had a significant effect in controlling and reducing runoff. Indeed, runoff was lower for plots previously under improved fallow than for plots under continuous cultivation (30 to 90% reduction). Lower runoff depth and runoff rate could be attributed to improvement in soil structure following the fallow phase. When farm-land is taken out of cultivation (natural fallow or planted fallow for several years, protected from fire and grazing), there is a combined build-up of SOC and soil aggregation (Ingram, 1990; Niang et al., 1996; IMPALA 2001; IMPALA 2002; Mutuo, 2004). Several studies have reported close relationship between runoff and soil aggregation (Le Bissonnais, 1996; Barthès et al., 2000; Barthès and Roose, 2002). In this study, improvement in WSA through fallowing was more important for the clay soil than for the sandy loam (+18% vs. +4% in average at 0-5 cm depth), and resulted in a greater reduction in runoff (-70 vs. -50% in average). For the sandy loam, the reduction in runoff after fallowing was mainly caused by a lower susceptibility to crusting. Indeed, the soil surface of the sandy loam crusted quickly (after 10 minutes), which greatly hindered infiltration. It is well established that surface sealing promotes overland flow (Bryan and De Ploey, 1983; Le Bissonnais, 1996; Rao et al., 1998) and is often prevailing on degraded soils. Values for resistance to penetration (RP) and shear (RS) indicated that cropping IF reduced crusting on the sandy loam (in average, RP and RS were reduced by 36 and 20%, respectively). Reduced RS and RP after biomass return have also been reported by Zeleke et al. (2004). However, for the clay soil of the present study, there was no significant difference in RP between treatments, and RS increased under IF-Tc (13%). Biomass return has also been reported to reduce bulk density (BD), and this was the case for the clay soil in this study. Differences in BD between treatments were not significant for the sandy loam at 0-5 cm depth. This is contrary to the findings of Zeleke et al. (2004), who found that biomass return caused a decrease in BD in a sandy soil but not in a clay soil. Reducing BD through biomass return has been related to enhanced infiltration rates, which this study confirmed.

4.2 Control of soil loss by improved fallows

Plots previously under IF generally experienced less soil loss. Improved fallows reduced soil loss by 68-84% on the clay soil and by 11-55% on the sandy loam, suggesting that improvement in soil structure due to IF was highly dependent on clay content and soil C. On the sandy loam, reduction in soil loss after fallowing seemed to depend mainly on reduction in runoff and transportability of detached particles, since topsoil properties such as C content, WSA and BD were not significantly affected. On the clay soil, reduction in soil loss after fallowing was more clearly associated with increases in C content and WSA and decrease in BD. A close relationship between topsoil WSA and soil susceptibility to runoff and erosion has also been reported by Barthès and Roose (2002). The great impact of fallowing on soil loss reduction was expected for the clay soil, due to its potential to form stable aggregates through the association between organic matter and clay particles. However, this study also showed that soil loss could be significantly reduced (-55%) on sandy loam when *Crotalaria grahamiana* was used for improved fallow.

The soil loss values measured in this study were in the same range as those reported by other studies which involved simulated rainfall (Merzouk and Blake, 1991; Meyers and Wagger, 1996). Soil loss measured from 1-m^2 plots primarily results from splash detachment by rain drops, and therefore gives an indication of interrill erosion. Scaling up soil loss values from 1-m^2 to slope and catchment scale has widely been discussed in literature. Merzouk and Blake (1991) found agreement between values of soil erodibility measured under simulated rainfall and the magnitude of soil erosion observed in the field. Other studies reported soil loss to be underestimated on microplots due to the short slope length (Le Bissonnais et al., 1998). However, simulated rainfall on microplots in the field enables detailed investigations on splash detachment and soil erodibility. Additionally, it can provide reliable indicators on runoff and soil loss for various soil types and land use systems.

4.3 Effect of no-tillage on soil properties, runoff and soil loss

No-tillage (NT) has in many instances resulted in improved soil structure. This has been attributed to the stabilization of the soil surface by increased SOC content and the accumulation of crop residues (Ingram and Fernandes, 2001; VandenBygaar et al., 2002), and by the lack of mechanical disturbance and its consequences on biological activity (Beare et al., 1994). In this study, changes in soil physical properties under NT were greatly dependent on soil texture. For the clay soil, topsoil C content and WSA were significantly greater under NT than under CT, but the increase was limited (27% for C content, 12% for WSA). For the sandy loam, topsoil C content and WSA did not differ significantly between NT and CT. Recent conversion from CT to NT probably explained the limited effects of tillage practices on soil properties. Indeed, measurements were carried out at the end of the first cropping season under NT, after many years under CT. Other studies have shown that improvement in soil physical properties under NT is a slow process, especially for degraded soils (Ingram and Fernandes, 2001). Rhoton et al. (2002) observed that topsoil SOC and WSA under NT had increased by 17% after four years and by 70% after 14 years. Thus greater increases in SOC and WSA under NT could be possible in the soils under study, but for longer durations. Soil bulk density did not differ either between tillage systems, which was contrary to the findings of Rhoton et al. (2002). These authors found BD to increase with the conversion from CT to NT. In the present study, bulk density varied according to soil type and depth, as also found by Arshad et al. (1999). Moreover, runoff and soil loss were not influenced by tillage in the present study, probably due to the recent conversion from CT to NT. Indeed, several studies have reported that runoff and soil loss were reduced under NT, and have related it to the accumulation of SOC under NT (Arshad et al., 1999; Franzluebbers, 2002; Rhoton et al., 2002). Similar results have been reported by Bradford and Huang (1994) from experiments under simulated rainfall. As regarded the present study, significant increases in topsoil C and WSA in the clay soil under NT indicated that runoff and soil loss could be reduced over time. Long-term experiments were needed to confirm this hypothesis.

4.4 Carbon content of sediments and enrichment ratio

Soil erosion has been found to decrease SOC by selective detachment and transport of fine particles (Watung et al. 1996; Wan and El-Swaify, 1997; Jacinthe et al., 2002; Lal, 2003), resulting in an enrichment of sediments in organic carbon (OC) relative to the *in situ* soil (Wan and El-Swaify 1997; Owens et al., 2002). This study also showed that sediments were enriched in OC. The enrichment ratio (ER) was higher for the sandy loam than for the clay soil (3.4 to 6.5 vs. 1.4 to 2.7), indicating that erosion was more selective on the former than on the latter. Sediments had a greater C/N ratio on the sandy loam (14-15, close to that of the topsoil and of the plants) than on the clay soil (10-12, lower than that of the topsoil), indicating that eroded C was less processed and less protected on the former than on the latter. These results suggested that eroded C on the clay soil was mainly in the form of processed organic matter protected within aggregates and removed with them, whereas eroded C on the sandy loam was mainly in the form of particulate organic matter.

4.5 Effect of land management on soil carbon losses and soil carbon stocks

C losses ranged from 0.12 to 1.95 g C m^{-2}, which corresponded with C losses measured by Jacinthe et al. (2002) under simulated rainfall on long-term NT plots. The present study demonstrated the potential of improved fallows to reduce runoff and soil loss (on 1-m^2 plots). A principal component analysis (PCA) showed that C losses could be explained by topsoil C content, WSA and resistance to shear (RS), and were thus influenced by soil type and land use. Indeed, topsoil C content, WSA and resistance to shear (RS) were lower and C losses greater in the sandy loam than in the clay soil. For the clay soil, increases in topsoil C content and WSA after improved fallows similarly resulted in smaller C losses. For the sandy loam, topsoil C content and WSA, as well as C losses, were less clearly affected by improved fallows, but increase in RS under no-tillage was associated with an increase in C losses. Thus increases in C losses were associated with decreases in topsoil C content and WSA for the clay soil (after fallow), but with increase in RS for the sandy loam (under NT).

Topsoil C stocks in the sandy loam and clay soil were less than those reported by Wilson (1997) and Nandwa (2001) for intensively cultivated soils in Kenya. The present study showed that improved fallows tended to increase topsoil C stocks, especially for the clay soil. The only significant increase in topsoil C stock resulting from fallow, which reached 22%, was for IF-Tc on clay soil, when stocks were calculated for an equivalent soil mass. The increase was not significant when stocks were calculated for the 0-10 cm depth layer (equivalent depth), emphasizing the importance of calculation at equivalent soil mass when discussing management-induced changes in SOC and nutrient storage, as recommended by Ellert and Bettany (1995). Additionally, NT resulted in an increase in topsoil C stock (at equivalent soil mass or depth) in the clay soil but not in the sandy loam, which confirmed the findings of Arshad et al. (1999). Their results showed greater C stocks under NT for a silty loam but no increase for a sandy loam.

5 Conclusion

The objectives of this study were to examine the effects of improved fallows (with *Crotalaria grahamiana* or *Tephrosia candida*) and no-tillage on runoff, soil and carbon losses for a sandy loam and a clay soil under maize-beans cultivation. The results showed that runoff, soil and C losses were smaller on the clay soil than on the sandy loam. They also showed that short-term improved fallows had the potential to reduce and control runoff, soil and carbon losses during the following cropping phase on both soil types, but that the reduction was greater on the clay soil than on the sandy loam. This was attributed to a build-up of topsoil C and WSA during the fallow phase, which was less important in average for the sandy loam than for the clay soil. Nevertheless, improved fallow with *Crotalaria grahamiana* was very effective in reducing runoff, soil and C losses on the sandy loam, mainly due to a reduction in crusting processes.

Soil carbon stocks were greater in the clay soil and were more clearly increased by improved fallows than in the sandy loam. The C enrichment ratio of sediments was significantly higher for the sandy loam, indicating that higher proportions of topsoil C were removed than on the clay soil. Sediment enrichment was not affected by treatments. Moreover, the proportion of topsoil C stock lost with sediments was much higher for the sandy loam than for the clay soil, but was not clearly affected by treatments.

No-tillage did not influence runoff and soil losses significantly. However, NT increased topsoil WSA, C content and C stock in the clay soil, and increased sediment enrichment ratio and C losses for the sandy loam. Conflicting results were seen for soil strength: under NT, soil resistance to shear and penetration decreased in the clay soil but increased in the sandy loam. However, all the results regarding tillage practices should be confirmed. Indeed, measurements were carried out at the end of the first cropping season under NT, following many years under CT. As improvement in soil properties under NT is considered a slow process in general, long-term experiments were needed to further examine the effects of NT on water, soil and C conservation.

Acknowledgements

The authors thank the European Commission (Project INCO-DEV n° ICA4-2000-30011), the Institut de Recherche pour le Développement (IRD), and the World Agroforestry Centre (ICRAF) for financing this research work.

References

Albrecht, A., and S.T. Kandji. 2003. Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems, and Environment* 99: 15-27.

Albrecht, A., L. Rangon, and P. Barret. 1992. Effets de la matière organique sur la stabilité structurale et la détachabilité d'un vertisol et d'un ferrisol (Martinique). *Cahiers ORSTOM, séroe Pédologie.* 27: 121-133.

Arshad, M.A., A.J. Franzluebbers, and R.H. Azooz. 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. *Soil and Tillage Research* 53: 41-47.

Asseline, J., and C. Valentin. 1978. Construction et mise au point d'un infiltromètre à aspersion. *Cahiers ORSTOM, série Hydrologie* 15: 321-349.

Barthès, B., A. Azontonde, B.Z. Boli, C. Prat, and E. Roose. 2000. Field-scale runoff and erosion in relation to topsoil aggregate stability in three tropical regions (Benin, Camerron, Mexico). *European Journal of Soil Science* 51: 485-495.

Barthès, B., and E. Roose. 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. *Catena* 47: 133-149.

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. *Soil Science Society of America Journal* 58: 777-786.

Bradford, J.M., and C. Huang. 1994. Interrill soil erosion as affected by tillage and residue cover. *Soil and Tillage Research* 31: 353-361.

Bryan, R.B., and J. De Ploey. 1983. Comparability of soil erosion measurements with different laboratory rainfall simulators. *Catena* 4: 33-56.

Cooper, P.J.M., R.R.B. Leaky, M.R. Rao, and L. Reynolds. 1996. Agroforestry and the mitigation of land degradation in the humid tropics and sub-humid tropics of Africa. *Experimental Agriculture* 32: 235-290.

Dixon, R.K. 1995. Agroforesry systems: sources or sinks of greenhouse gases? *Agroforestry Systems* 31: 99-116.

Doran, J.W., M. Sarrantonio, and M.A. Liebig. 1996. Soil health and sustainability. *Advances in Agronomy* 56: 1-54.

Ellert, B.H., and J.R. Bettany. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Sciences* 75: 529-538.

Feller C., A. Albrecht, and D. Tessier.1996. Aggregation and organic carbon storage in kaolinitic and smectitic tropical soils. p. 309-360. In: M.R. Carter and B.A. Stewart (eds.), *Structure and Organic Matter Storage in Agricultural Soils*, CRC Press, Boca Raton, FL.

Franzluebbers, A.J. 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage Research* 75: 1-9.

IMPALA. 2001. *Project Report Year 1 (INCO-DEV Project No ICA4-CT-2000-30011).* World Agroforestry Centre, Nairobi, Kenya.

IMPALA. 2002. *Project Report Year 2 (INCO-DEV Project No ICA4-CT-2000-30011)*. World Agroforestry Centre, Nairobi, Kenya.

Ingram, J. 1990. The role of trees in maintaining and improving soil productivity – a review of the literature. p. 243-303. In: Prinsley R.T. (ed.), *Agroforestry for Sustainable Production, Economic Implications*. Commonwealth Science Council, London.

Ingram, J.S.I., and E.C.M. Fernandes. 2001. Managing carbon sequestration in soils: concepts and terminology. *Agriculture, Ecosystems and Environment* 87: 111-117.

Jacinthe, P.A., R. Lal, and J.M. Kimble. 2002. Carbon dioxide evolution in runoff from simulated rainfall on long-term no-till and plowed soils in southwestern Ohio. *Soil and Tillage Research* 66: 23-33.

Kursten, E., and P. Burschel. 1993. CO_2-mitigation by agroforestry. *Water, Air, and Soil Pollution* 70: 533-544.

Lal. R. 2003. Soil erosion and the global carbon budget. *Environment International* 29: 437-450.

Le Bissonnais, Y. 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science* 47: 425-437.

Le Bissonnais, Y., H. Benkhadra, V. Chaplot, D. Fox, D. King, and J. Daroussin. 1998. Crusting, runoff and sheet erosion on silty loamy soils at various scales and upscaling from m^2 to small catchment. *Soil and Tillage Research* 46: 69-80.

McCarty, G.W., and J.C. Ritchie. 2002. Impact of soil movement on carbon sequestration in agricultural ecosystems. *Environmental Pollution* 116: 423-430.

Merzouk, A., and G.R. Blake. 1991. Indices for the estimation of interrill erodibility of Moroccan soils. *Catena* 18: 537-559.

Meyers, J.L., and M.G. Wagger. 1996. Runoff and sediment loss from three tillage systems under simulated rainfall. *Soil and Tillage Research* 39: 115-129.

Mutuo, P. 2004. *Potential of Improved Tropical Legume Fallows and Zero Tillage Practices for Soil Organic Carbon Sequestration*. Ph.D. Dissertation, Imperial College, University of London.

Nandwa, S.M. 2001. Soil organic carbon (SOC) management for sustainable productivity of cropping and agroforestry systems in Eastern and Southern Africa. *Nutrient Cycling in Agroecosystems* 61: 143-158.

Niang, A., J. De Wolf, M. Nyasimi, T.S. Hansen, R. Rommelse, and K. Mwendwa. 1998. *Soil Fertility Recapitalisation and Replenishment Project in Western Kenya. Progress Report February 1997 - July 1998. Pilot Project Report No. 9.* Regional Agroforestry Research Centre, Maseno, Kenya.

Niang, A., S. Gathumbi, and B. Amadalo. 1996. The potential of short duration improved fallow for crop production enhancement in the highlands of western Kenya. *East African Agriculture and Forestry Journal* 62: 103-114.

Owens, L.B., R.W. Malone, D.L. Hothem, G.C. Starr, and R. Lal. 2002. Sediment carbon concentration and transport from small watersheds under various conservation tillage practices. *Soil and Tillage Research* 67: 65-73.

Rao, K.P.C, T.S. Steenhais, A.L. Cogle, S.T. Srinivasan, D.F. Yule, and G.D. Smith. 1998. Rainfall infiltration and runoff from an Alfisol in semi-arid tropical India. I. No-till systems. *Soil and Tillage Research* 48: 51-59.

Rhoton, F.E., M.J. Shipitalo, and D.L. Lindbo. 2002. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. *Soil and Tillage Research* 66: 1-11.
Thioulouse, J., D. Chessel, S. Doledec, and J.M. Olivier. 1997. ADE4: a multivariate analysis and geographical display software. *Statistics and Computing* 7: 75-83.
VandenBygaart, A.J., X.M.Yang, B.D. Kay, and J.D. Aspinall. 2002. Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. *Soil and Tillage Research* 65: 231-241.
Van Roode, M. 2000. *The Effects of Vegetative Barrier Strips on Surface Runoff and Soil Erosion in Machakos, Kenya*. Ph.D. Dissertation, Universiteit Utrecht.
Wan, Y., and S.A. El-Swaify. 1997. Flow induced transport and enrichment of erosional sediment from a well-aggregated and uniformly-textured Oxisol. *Geoderma* 75: 251-265.
Watung, R.L., R.A. Sutherland, and S.A. El-Swaify. 1996. Influence of rainfall energy flux density and antecedent soil moisture content on splash transport and aggregate enrichment ratios for a Hawaiian Oxisol. *Soil Technology* 9: 251-272.
Zeleke, T.B., M.C.J. Grevers, B.C. Si, A.R. Mermut, and S. Beyene. 2004. Effect of residue incorporation on physical properties of the surface soil in the South Central Rift Valley of Ethiopia. *Soil and Tillage Research* 77: 35-46.

Table titles and figure captions

Table 1. Topsoil characteristics (0-15 cm depth) at the beginning of the experiment for the two study sites, Masai and Luero (Kenya).

Table 2. Effect of cropping system on soil organic carbon (SOC), C/N ratio, bulk density and soil carbon stock for the sandy loam and the clay soil.

Table 3. Effect of cropping system on water stable aggregates (WSA) and soil strength for the sandy loam and the clay soil.

Table 4. Effect of cropping system on runoff and soil loss for the sandy loam and the clay soil.

Table 5. Effect of cropping system on sediment carbon content, sediment C/N, ratio of sediment enrichment in carbon and carbon losses for the sandy loam and the clay soil.

Figure 1. Cropping sequences for the cropping systems under study (black represents the cropping phase and grey the fallow period; for CC the fallow is a natural fallow).

Figure 2. Results from principal component analysis (PCA) on soil carbon losses: Figure 2a. F1-F2 correlation circle of variables (RP and RS are soil resistance to penetration and shear, respectively, and WSA water stable aggregates);

Figure 2b. Factorial map of treatments.

No 1-6 sandy loam: (1) CC-CT, (2) CC-NT, (3) IF-Tc-CT, (4) IF-Tc-NT, (5) IF-Cg-CT, (6) IF-Cg-NT

No 7-12 clay soil: (7) CC-CT, (8) CC-NT, (9) IF-Tc-CT, (10) IF-Tc-NT, (11) IF-Cg-CT, (12) IF-Cg-NT