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Highlights

Agriculture, Ecosystems and Environment xx (2012) xxx–xxx

Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity

B.K. Paul*, B. Vanlauwe, F. Ayuke, A. Gassner, M. Hoogmoed, T.T. Hurisso, S. Koala, D. Lelei, T. Ndabamenye, J. Six, M.M. Pulleman

► Conventional tillage negatively affected soil aggregate stability. ► CA did not increase soil C content at 0–30 cm depth after 11 cropping seasons. ► CA did not increase physical C protection in soil aggregate fractions. ► Reduced tillage without residue retention suppressed soybean yields. ► Future research should establish critical minimum residue retention levels.

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Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity

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A B S T R A C T

Conservation agriculture is widely promoted for soil conservation and crop productivity increase, although rigorous empirical evidence from sub-Saharan Africa is still limited. This study aimed to quantify the medium-term impact of tillage (conventional and reduced) and crop residue management (retention and removal) on soil and crop performance in a maize–soybean rotation. A replicated field trial was started in sub-humid Western Kenya in 2003, and measurements were taken from 2005 to 2008. Conventional tillage negatively affected soil aggregate stability when compared to reduced tillage, as indicated by lower mean weight diameter values upon wet sieving at 0–15 cm ($P_T < 0.001$). This suggests increased susceptibility to slaking and soil erosion. Tillage and residue management alone did not affect soil C contents after 11 cropping seasons, but when residue was incorporated by tillage, soil C was higher at 15–30 cm (P_{T*R} = [illegible]7). Lack of treatment effects on the C content of different aggregate fractions indicated that reduced tillage and/or residue retention did not increase physical C protection. The weak residue effect on aggregate stability and soil C may be attributed to insufficient residue retention. Soybean grain yields tended to be suppressed under reduced tillage without residue retention, especially in wet seasons ($P_{T*R} = 0.070$). Consequently, future research should establish, for different climatic zones and soil types, the critical minimum residue retention levels for soil conservation and crop productivity.

1. Introduction

Agriculture in Sub-Saharan Africa (SSA) is faced with the challenge to increase productivity while conserving natural resources. More than 80% of the land has medium to low agricultural potential due to low inherent soil fertility (Eswaran et al., 1997). Moreover, approximately 65% of agricultural land in SSA has been degraded through human activities such as soil tillage and continuous cropping with insufficient mineral and organic fertilizer application (Oldeman et al., 1991). Soil fertility depletion and degradation are seen as major biophysical causes of stagnating staple crop yields in SSA (Sanchez et al., 1997).

Conservation agriculture (CA) is promoted for its potential contribution to smallholder agricultural production and reversal of soil degradation in SSA (Erenstein et al., 2008). CA has three fundamental yet intertwined principles: (i) continuous minimum mechanical soil disturbance; (ii) permanent organic soil cover; and (iii) diversification of crops grown in sequence or associations (FAO, 2008). Potential biophysical benefits include improved soil aggregation, leading to lower wind and water erosion, and improved water infiltration and water retention, increased soil organic matter (SOM) content and C sequestration, and increased and/or more stable crop yields (Mrabet, 2002; Hobbs, 2007). However, full CA adoption is extremely low among smallholder farmers in SSA (Lal, 2007;

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Derpsch et al., 2010). It has been reported that smallholder farmers rarely adopt all three CA principles together, due to resource constraints and trade-offs with other farm activities, especially with regard to the availability of crop residues, seeds, land, labor, cash or credit (Wall, 2007; Kassam et al., 2009).

Soil aggregate stability and soil organic matter (SOM) are key indicators for soil quality and environmental sustainability in agroecosystems. Firstly, stable aggregates can physically protect SOM against rapid decomposition (Pulleman and Marinissen, 2004; Six et al., 2004; Bossuyt et al., 2005), and reduce soil erosion, surface crusting and runoff (Le Bissonnais, 1996; Barthes and Roose, 2002). Secondly, SOM binds mineral particles into aggregates (Tisdall and Oades, 1982), stimulates the activities of soil biota (Six et al., 2004; Ayuke et al., 2011b), maintains favorable physicochemical conditions such as cation exchange capacity (CEC) (Vanlauwe et al., 2002) and stores soil organic carbon (SOC) crucial to climate change mitigation (Lal, 2011). Both tillage and residue management can decisively influence aggregate stability and SOM. Tillage has been reported to decrease soil aggregation and SOM by accelerating the turnover of aggregate-associated SOM (Six et al., 1999). Residue retention can increase soil aggregation when compared to no-input systems, although the magnitude depends on residues quantity and quality (Chivenge et al., 2011). Further, residues contribute to the build up of SOM, which can work synergistically with mineral fertilizers to increase crop biomass and, subsequently, organic matter returns to the soil (Vanlauwe et al., 2002; Bationo et al., 2007).

Despite the considerable interest in CA, rigorous empirical evidence of the benefits of CA in SSA is limited and inconsistent. Given that smallholders in SSA rarely fully adopt all three CA principles, it appears imperative to thoroughly assess the effects of, and interactions between, each of the CA components (Gowing and Palmer, 2008; Giller et al., 2009, 2011). Therefore, the aim of this study was to quantify the effects of CA components on soil quality and crop yields. More specifically, the objectives were:

1. To determine the single and interactive effects of tillage and residue management on soil aggregate stability and soil (aggregate) organic C over time.
2. To determine the single and interactive effects of tillage and residue management on crop yields over time.

2. Materials and methods

2.1. Site description

This study was executed in an existing long-term tillage trial in Nyabeda in sub-humid Western Kenya. The field experiment was established in March 2003 and has been managed by researchers of the African Network for Soil Biology and Fertility (AfNet) of the Tropical Soil Biology and Fertility (TSBF) research area of CIAT. The site is located at an altitude of 1420 m asl, latitude 0°06′N and longitude 34°24′E, with 2% field slope. A mean annual rainfall of 1800 mm is distributed over two rainy seasons: the long rainy season lasts from March until August and the short rainy season from September until January. Cumulative seasonal rainfall during the experimental period is presented in Fig. 1. Maize is the main staple crop in the area, normally grown as a monocrop or in association with groundnut and beans, sown broadcast. Smallholder subsistence farming is most common and average farm sizes vary between 0.3 and 3 ha. Soybean has been adopted more recently as a cash crop (Kihara, 2009). Prior to the establishment of the trial, native grasses and shrubs dominated the experimental area. The soil was classified as a Ferrasol (FAO, 1998) with 64% clay, 15% sand and 21% silt. Average soil chemical characteristics of the top 20 cm soil depth included: pH (H_2O) 5.1, 13.5 mg C g^{-1} soil, 1.5 mg total N g^{-1}, 2.99 mg P kg^{-1}, 0.1 me extractable K 100 g^{-1}, 4.7 cmolc Ca kg^{-1}, and 1.7 cmolc Mg kg^{-1} (Kihara, 2009).

2.2. Experimental design and trial management

The trial was set up in a randomized block design with tillage and crop residue retention as main factors. Each factor had two levels: conventional tillage (+T) or reduced tillage (−T) and residue retention (+R) or residue removal (−R). A factorial combination of the factors resulted in four treatments, which were replicated four times in separate blocks. The crop rotation consisted of soybean (*Glycine max* L.) during short rains and maize (*Zea mays* L.) during long rains. Maize was planted at 75 cm row spacing and 25 cm planting density, and soybean at 75 cm and 5 cm respectively. Individual plots measured 7 m × 4.5 m, and all of them were fertilized at 60 kg ha^{-1} N (urea), 60 kg ha^{-1} P (Triple Super Phosphate) and 60 kg ha^{-1} K (Muriate of Potash) per growing season. All fertilizers were applied by mixing fertilizer with soil in the planting hole, placing maize or soybean seed on top and covering it lightly with soil. Under conventional tillage (+T), the seedbed was prepared by hand hoeing to 15 cm soil depth. Weeding was performed three times per season, using the hand hoe. Under reduced tillage (−T), a 3 cm deep seedbed was prepared with the hand hoe. Weeding was performed three times per season by hand pulling. After harvest, maize residues were collected, dried, chopped and stored during the dry season for approximately one month. With the beginning of the short rains, maize residues were reapplied at a rate of 2 Mg ha^{-1} (+R), and were either incorporated by conventional tillage (+T) or remained at the soil surface as mulch under reduced tillage (−T) just before soybean was planted. Since soybeans drop leaves prior to grain maturity, soybean residues (leaves and stems) always remained in the field after harvest, irrespective of treatment. These soybean residues were then either incorporated (+T) or remained at the soil surface (−T).

2.3. Soil analyses: aggregate fractionation and C

During the short rainy season of 2005 (n = 4) and the long rainy seasons of 2006 (n = 4), 2007 (n = 3) and 2008 (n = 4), undisturbed soil samples were taken from all treatments at two soil depths (0–15 cm and 15–30 cm). This corresponded to the 6th, 7th, 9th and 11th cropping season after trial establishment. Representative subsamples of approximately 500 g were gently passed through a 10 mm sieve by breaking the soil along natural planes of weakness. After air drying, the soil was split up in four fractions by the wet sieving method described by Elliott (1986): (a) large macroaggregates (LM; >2000 μm), (b) small macroaggregates (SM; 250–2000 μm), (c) microaggregates (Mi; 53–250 μm), (d) silt and clay sized particles (SC; ≤53 μm). 80 g of air-dried soil was evenly spread on a 2 mm sieve, which was placed in a recipient filled with deionized water and left to slake. After 5 min, the sieve was manually moved up and down 50 times in 2 min. The procedure was repeated passing the material on to a 250 μm and 53 μm sieve. Soil aggregates retrieved at each sieve were carefully backwashed into beakers, oven-dried at 60 °C for 48 h, weighed back and stored for C and N analysis. SC was calculated from the total volume of the suspension and the volume of the subsample. Mean weight diameter (MWD) was determined as the sum of the weighted mean diameters of all fraction classes.

Total soil C and N were analyzed in whole soil and aggregate fractions. Sub-samples were oven-dried, ground and sent to UC Davis, California, USA. Total C and N values were determined with a Dumas combustion method, using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK).

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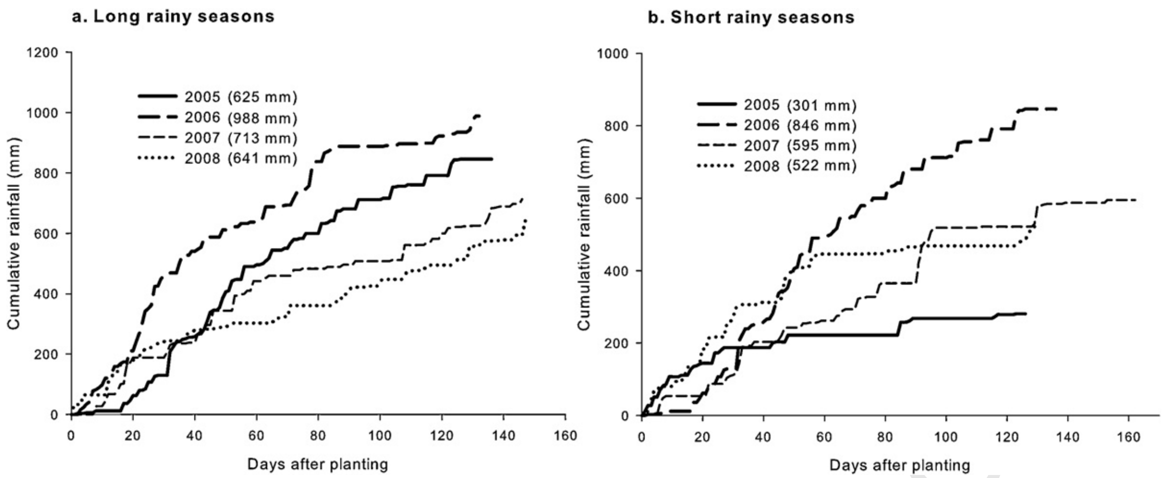

Fig. 1. Seasonal cumulative rainfall recorded in Nyabeda, Western Kenya during the long rainy seasons (a) and short rainy seasons (b) from 2005 to 2008. Maize is grown in the long rainy season (March/April–August) and soybean during the short rainy season (August/September–January/February).

2.4. Crop yield measurements

Maize was harvested from each plot at maturity, leaving one row (75 cm) at each side of the plot and two plants (50 cm) at the end of each row to exclude edge effects. Cobs were separated from stover, counted and fresh weight was determined. After air-drying, grains were separated from the cobs, oven-dried at 65 °C for 48 h and dry weight was determined. Maize biomass and grain dry weight was reported on an oven-dry basis. Soybean was harvested from each plot at 95% maturity, excluding one row (75 cm) at each side of the plot and two plants (50 cm) at the end of each row to discount edge effects. Grains were separated from husks and haulms (stover) and fresh weight was determined. After air-drying, grains, husk and haulms were oven-dried at 65 °C for 48 h and dry weight was determined. Soybean biomass and grain dry weight was reported on an oven-dry basis. Daily rainfall was measured with a rainfall gauge in the experimental field.

2.5. Statistical analyses

Data points farther than their interquartile ranges from the nearer edge of the box, as identified by SPSS 19.0.0 (2010) box plots, were regarded as extreme outliers and omitted before further analysis. Analysis of variance was carried out with GenStat 14.1 (2011), and soil data were analyzed independently for two soil depths (0–15 cm and 15–30 cm). A repeated measurements mixed model was used to test the influence of year, tillage and residue (fixed factors) and their interactions on soil aggregation, soil (aggregate) C and crop yields. The autocorrelations of year and sampling plot (repeated measurement) were entered as random factors. An unstructured covariance matrix was used to fit the model. Means are presented with standard errors. A *P*-value of 0.05 or smaller was considered significant.

3. Results

3.1. Aggregate fractions

At 0–15 cm soil depth, amounts of LM were consistently lower under conventional tillage compared to reduced tillage. Mean amounts were 6.8 g 100 g^{-1} vs. 15.4 g 100 g^{-1} across years and residue treatments ($P_T < 0.001$) (Fig. 2a). Differences in the amount of SM were smaller, with 47.2 g 100 g^{-1} vs. 49.1 g 100 g^{-1} ($P_T < 0.001$), while amounts of Mi and SC were higher under conventional tillage with 37.7 g 100 g^{-1} vs. 28.1 g 100 g^{-1} and 8.7 g 100 g^{-1} vs. 7.5 g 100 g^{-1} (both $P_T < 0.001$). These differences in aggregate size distribution were reflected in a consistently lower MWD under conventional tillage ($P_T < 0.001$), with means of 0.9 mm vs. 1.3 mm for conventional and reduced tillage respectively (Fig. 3a). No residue effect on MWD was found, but the T*R interaction was significant ($P_{T*R} = 0.004$) (Fig. 3a). The influence of year was significant for MWD and all fractions (Figs. 2a and 3a).

At 15–30 cm soil depth, amounts of SM were consistently lower each year in conventional tillage relative to reduced tillage. Mean values across years and residue treatments were 48.2 g 100 g^{-1} vs. 49.0 g 100 g^{-1}, respectively ($P_T = 0.005$) (Fig. 2b). Mi and SC fractions were relatively more abundant in conventional tillage than in reduced tillage with 19.0 g 100 g^{-1} vs. 15.2 g 100 g^{-1} and 4.7 g 100 g^{-1} vs. 3.6 g 100 g^{-1}, respectively (both at $P_T < 0.001$). Residue retention under conventional tillage led to a lower average MWD (1.7 mm) than under all other treatments (2.1–2.2 mm) ($P_T = 0.027$, $P_{T*R} = 0.009$) (Fig. 3b). The influence of year was significant for MWD and all fractions except SM (Figs. 2b and 3b).

These data show that the MWD was higher at 15–30 cm (2.0 mm on average) than at 0–15 cm (1.1 mm) (Fig. 3a and b).

3.2. Total soil organic C and aggregate fraction C

At 0–15 cm, neither tillage nor residue management had a significant effect on total soil C ($P_T = 0.087$; $P_R = 0.440$) (Table 1). The only effect of tillage or residue on aggregate C content was a decrease of the C content in the SC fraction due to tillage ($P_T = 0.045$) (Table 1).

At 15–30 cm, neither tillage nor residue affected total soil C, but a significant T*R interaction was found ($P_{T*R} = 0.037$) (Table 1). Soil C was higher under residue retention with conventional tillage, but not with reduced tillage. As a consequence, +T+R corresponded to the highest average soil C content (18.8 mg C g^{-1} soil) and −T−R showed the lowest average soil C content across four years of measurement (16.1 mg C g^{-1} soil). C contents of the LM ($P_T = 0.003$), SM ($P_T = 0.008$), and Mi ($P_T = 0.049$) fractions were higher under conventional tillage than under reduced tillage, and for the LM ($P_{T*R} = 0.043$) and Mi ($P_{T*R} = 0.056$) fractions the interaction effect was (marginally) significant (Table 1).

3.3. Crop yields

Neither tillage nor residue management significantly affected maize grain yields (Fig. 4a). Average grain yield across four years was lowest for −T−R (3.6 t ha^{-1}), while yields were comparable for the other three treatments (4.3–4.5 t ha^{-1}). The influence of year

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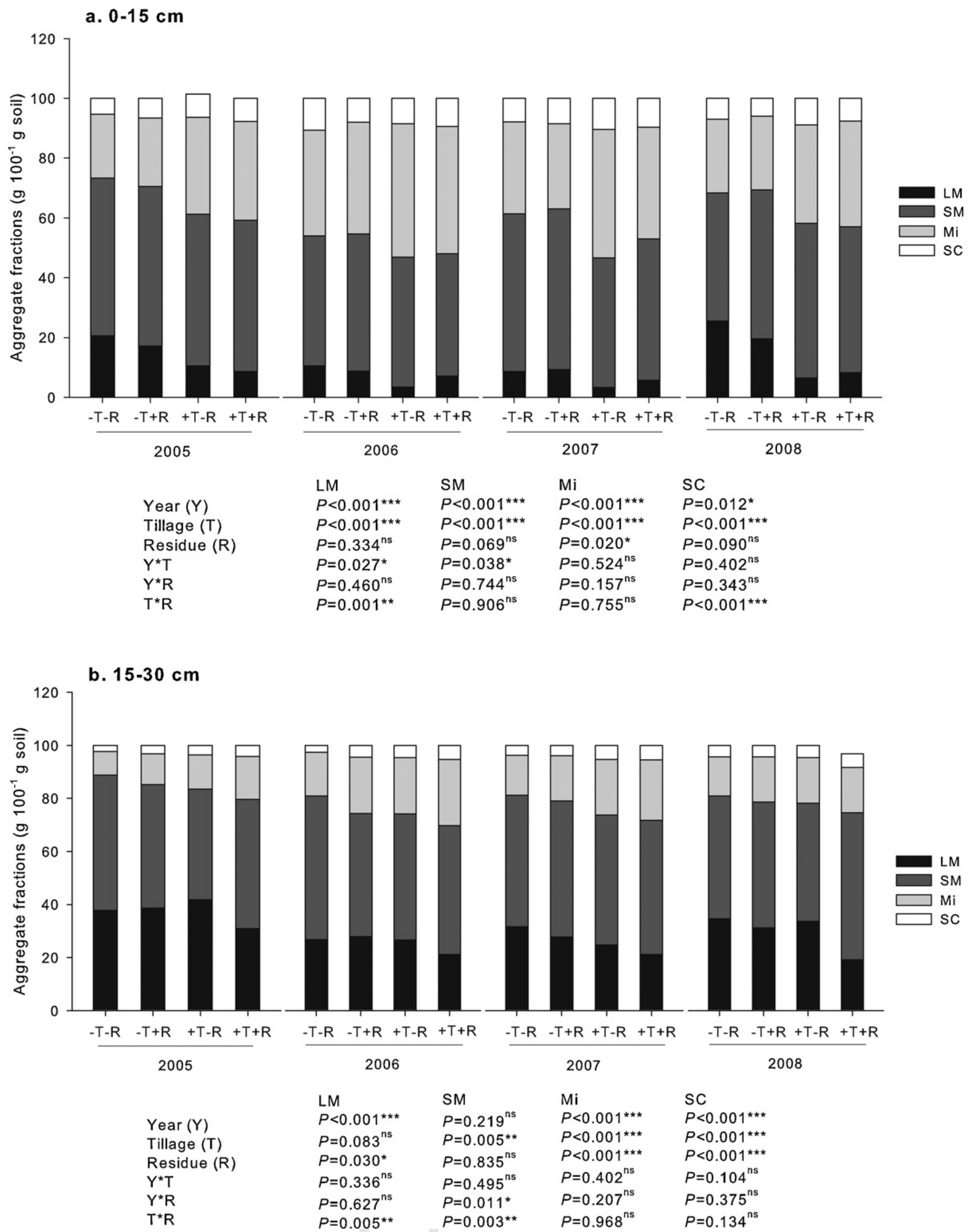

Fig. 2. Aggregate fractions from 2005 to 2008 at 0–15 cm (a) and 15–30 cm (b) soil depth. Codes refer to combinations of reduced tillage (−T), conventional tillage (+T), residue removal (−R) and residue retention (+R). Aggregate fractions include large macroaggregates (a; LM; >2000 μm), small macroaggregates (b; SM; 250–2000 μm), microaggregates (c; Mi; 53–250 μm) and silt and clay (d; SC; <53 μm). Levels of significance indicate single and interactive effects of year (Y), tillage (T) and residue (R) on aggregate fractions over all years. *P* values refer to the following levels of significance: *<0.05, **<0.01, ***<0.001, and [ns]not significant.

was highly significant ($P_Y < 0.001$) (Fig. 4a). Total biomass yield followed the same pattern as grain yield; average total maize biomass across four years was lowest for −T−R (8.2 t ha^{-1}), while it ranged from 8.6 to 9.6 t ha^{-1} for the other treatments. However, management effects were not significant (data not presented).

Similarly, no significant tillage or residue effect on soybean grain yield was found (Fig. 4b). Average yield across the four years was lowest for −T−R (0.45 t ha^{-1}), while yields were comparable for the other three treatments (0.81–0.89 t ha^{-1}). This corresponded on average to 46% less soybean yield from −T−R than from the other treatments. The yield difference was especially strong in 2006 with a relative reduction in soybean yield of 53% under −T−R. This was reflected in marginally significant interaction between tillage and residue ($P_{T*R} = 0.070$) and year and tillage ($P_{Y*T} = 0.067$). The

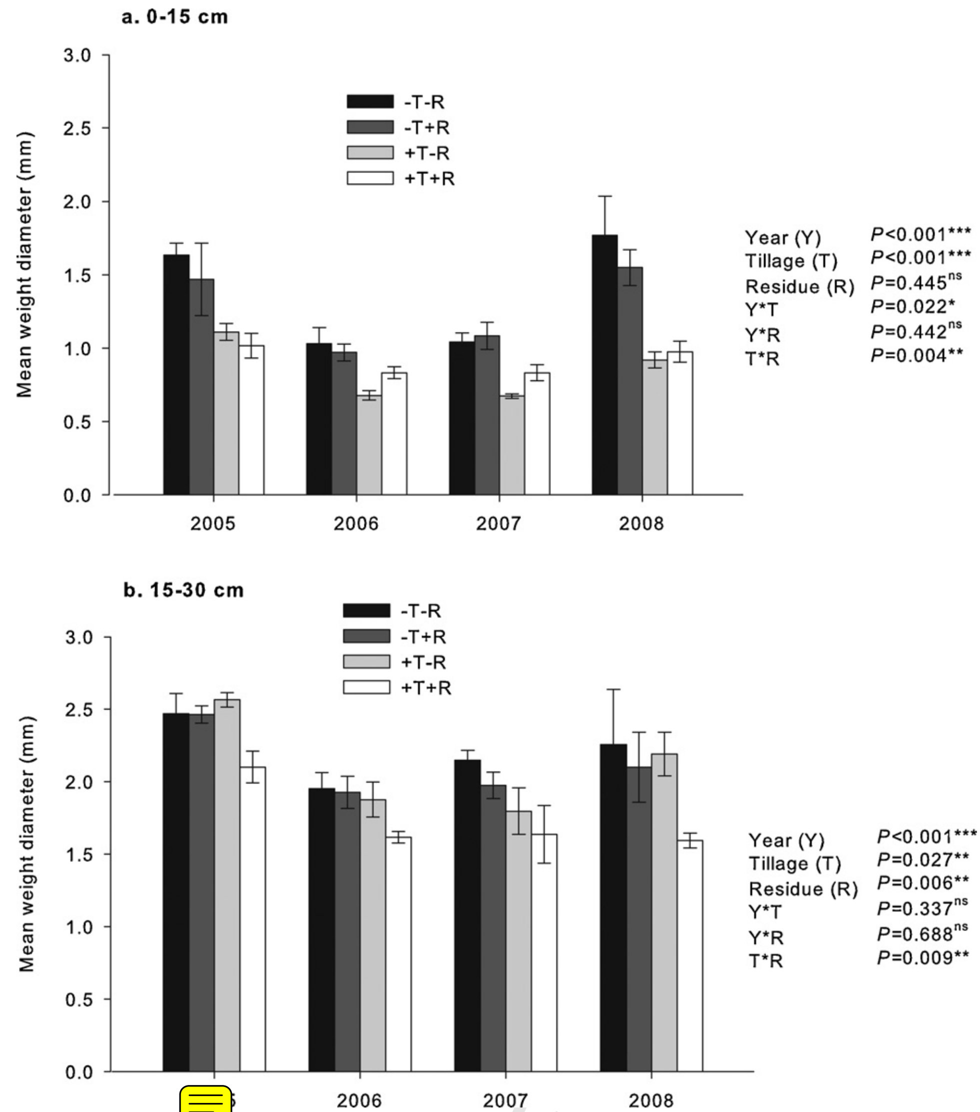

Fig. 3. Aggregate mean weight diameter (MWD) from 2005 to 2008 at 0–15 cm (a) and 15–30 cm (b) soil depth. MWD is the sum of the weighted mean diameters of all fraction classes. Error bars indicate standard errors. Levels of significance indicate single and interactive effects of year (Y), tillage (T) and residue (R) on MWD over all years. *P* values refer to the following levels of significance: *<0.05, **<0.01, ***<0.001, and ns not significant.

influence of year was highly significant ($P_Y < 0.001$) (Fig. 4b). Total biomass yields followed the same pattern as grain yields. The average total soybean biomass across four years was lowest for −T−R (1.6 t ha^{-1}), and ranged from 2.4 to 2.6 t ha^{-1} for the other treatments. This was reflected in a significant interaction between tillage and residue ($P_{T*R} = 0.023$) (data not presented).

4. Discussion

4.1. Tillage and residue management effects on soil aggregation

Reduced tillage resulted in a higher soil aggregate stability compared conventional tillage (Fig. 3a and b). This effect was mainly caused by a breakup of LM into Mi and SC fractions (Fig. 2a and b). These observations are consistent with findings from Eastern and Western Kenya (Gicheru et al., 2004; Kihara et al., 2011) and Zambia (Thierfelder and Wall, 2010), where minimum tillage resulted in higher aggregate MWD. Water stable aggregation has frequently been shown to reduce the susceptibility to runoff and soil erosion (Le Bissonnais, 1996; Barthes and Roose, 2002).

The effect of residue management on soil aggregation in this study cannot be explained with certainty (Fig. 3a and b). At 0–15 cm, residue retention decreased MWD under reduced tillage, while at 15–30 cm residue retention decreased MWD when incorporated by conventional tillage. These findings contradict other studies, which have shown that low quality organic residues combined with fertilizer improved aggregate stability (Blair et al., 2005; Abiven et al., 2009; Chivenge et al., 2011). Possible reasons include biological activity of soil ecosystem engineers that produce smaller aggregates. While the beneficial influence of earthworms on aggregate formation is well known, little quantitative information is available on the contribution of subterranean termites to soil aggregation (Kooyman and Onck, 1987; Lavelle et al., 1992; Six et al., 2004). However, it is evident that termites influence the soil microstructure through formation of fecal and oral pellets in the microaggregate size class (Kooyman and Onck, 1987; Fall et al., 2001).

The annual variation of soil aggregate data points to an influence of weather conditions. A destructive effect of rainfall and wetting and drying on soil aggregates was also found by Guto et al. (2011). If the annual variation is part of a time trend can only be

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Table 1
Total soil organic C (mg C g^{-1} soil) and aggregate fraction C (mg C g^{-1} fraction) from 2005 to 2008 at 0–15 cm and 15–30 cm soil depth. Aggregate fractions include large macroaggregates (LM; >2000 μm), small macroaggregates (SM; 250–2000 μm), micro aggregates (Mi; 53–250 μm) and silt and clay (SC; <53 μm). Values are means followed by standard errors between parentheses. *P* values refer to the following levels of significance: *<0.05, **<0.01, ***<0.001, and ^{ns}not significant.

	Depth 0–15 cm					Depth 15–30 cm				
	Total (mg C g^{-1} soil)	Aggregate fraction C (mg C g^{-1} fraction)				Total (mg C g^{-1} soil)	Aggregate fraction C (mg C g^{-1} fraction)			
		LM	SM	Mi	SC		LM	SM	Mi	SC
2005										
−T−R	20.1 (±0.5)	–	–	–	–	14.6 (±1.3)	–	–	–	–
−T+R	21.3 (±0.7)	–	–	–	–	16.9 (±0.2)	–	–	–	–
+T−R	21.1 (±0.4)	–	–	–	–	18.0 (±0.5)	–	–	–	–
+T+R	20.3 (±0.3)	–	–	–	–	18.1 (±1.0)	–	–	–	–
2006										
−T−R	20.1 (±0.4)	20.1 (±0.7)	19.8 (±0.5)	21.2 (±0.3)	24.5 (±1.1)	16.1 (±0.7)	16.1 (±0.9)	15.9 (±0.9)	17.3 (±1.0)	26.0 (±1.5)
−T+R	21.3 (±0.6)	21.2 (±0.5)	20.1 (±0.7)	21.6 (±0.4)	23.2 (±0.5)	18.4 (±0.4)	17.7 (±0.3)	18.1 (±0.8)	19.6 (±0.7)	25.3 (±1.2)
+T−R	20.1 (±0.5)	21.1 (±1.4)	19.6 (±1.1)	20.4 (±0.7)	24.2 (±0.6)	18.4 (±0.9)	18.3 (±0.6)	18.5 (±1.1)	19.1 (±1.2)	24.0 (±0.7)
+T+R	19.9 (±0.2)	19.5 (±1.1)	19.2 (±0.5)	20.8 (±0.1)	22.5 (±0.6)	18.1 (±0.5)	18.0 (±0.6)	17.9 (±0.1)	19.3 (±0.3)	23.2 (±0.5)
2007										
−T−R	19.8 (±0.3)	21.1 (±0.3)	19.6 (±0.6)	21.1 (±0.5)	25.2 (±1.5)	17.6 (±0.9)	16.9 ±(0.6)	17.5 (±0.5)	18.5 (±0.9)	22.3 (±1.6)
−T+R	20.6 (±1.8)	22.7 (±2.2)	21.2 (±1.1)	21.5 (±0.6)	23.4 (±0.5)	17.8 (±0.7)	17.8 (±0.4)	17.8 (±0.5)	19.1 (±0.3)	23.1 (±1.0)
+T−R	20.0 (±0.7)	21.5 (±1.0)	19.4 (±0.4)	21.1 (±0.8)	21.6 (±0.8)	18.4 (±0.4)	17.8 (±0.4)	18.1 (±0.5)	19.3 (±0.2)	25.0 (±2.2)
+T+R	20.3 (±0.6)	22.1 (±1.5)	19.8 (±0.6)	21.0 (±0.4)	22.7 (±0.7)	18.9 (±0.9)	16.3 (±1.1)	16.8 (±0.5)	18.2 (±0.4)	22.7 (±0.6)
2008										
−T−R	20.4 (±0.6)	21.5 (±0.7)	20.7 (±0.6)	21.1 (±1.4)	22.5 (±1.2)	16.0 (±1.0)	15.2 (±0.4)	15.5 (±1.4)	17.5 (±0.7)	23.0 (±2.0)
−T+R	21.6 (±1.1)	22.1 (±2.2)	21.6 (±1.6)	20.7 (±1.0)	25.7 (±0.8)	18.3 (±1.2)	17.7 (±1.1)	17.5 (±1.1)	18.8 (±0.6)	24.2 (±0.9)
+T−R	20.4 (±0.6)	20.1 (±0.8)	20.4 (±0.9)	20.1 (±0.7)	23.2 (±0.8)	18.5 (±0.9)	18.5 (±1.1)	18.7 (±1.1)	20.0 (±1.2)	23.8 (±0.7)
+T+R	21.8 (±0.3)	23.1 ±(1.4)	21.1 (±0.4)	20.4 (±0.2)	22.9 (±0.2)	20.2 (±0.4)	19.7 (±0.4)	20.4 (±1.0)	19.8 (±0.5)	22.9 (±0.6)
Year	0.039*	0.257^{ns}	0.071^{ns}	0.460^{ns}	0.841^{ns}	0.058^{ns}	0.611^{ns}	0.727^{ns}	0.856^{ns}	0.202^{ns}
Tillage	0.087^{ns}	0.759^{ns}	0.230^{ns}	0.144^{ns}	0.045*	0.191^{ns}	0.003**	0.008**	0.049*	0.524^{ns}
Residue	0.440^{ns}	0.243^{ns}	0.285^{ns}	0.668^{ns}	0.670^{ns}	0.104^{ns}	0.059^{ns}	0.155^{ns}	0.201^{ns}	0.591^{ns}
Year * Tillage	0.059^{ns}	0.990^{ns}	0.944^{ns}	0.850^{ns}	0.425^{ns}	0.187^{ns}	0.031*	0.071^{ns}	0.259^{ns}	0.227^{ns}
Year * Residue	0.340^{ns}	0.491^{ns}	0.625^{ns}	0.901^{ns}	0.085^{ns}	0.493^{ns}	0.139^{ns}	0.248^{ns}	0.398^{ns}	0.838^{ns}
Tillage * Residue	0.097^{ns}	0.835^{ns}	0.494^{ns}	0.951^{ns}	0.724^{ns}	0.037*	0.043*	0.195^{ns}	0.056^{ns}	0.261^{ns}

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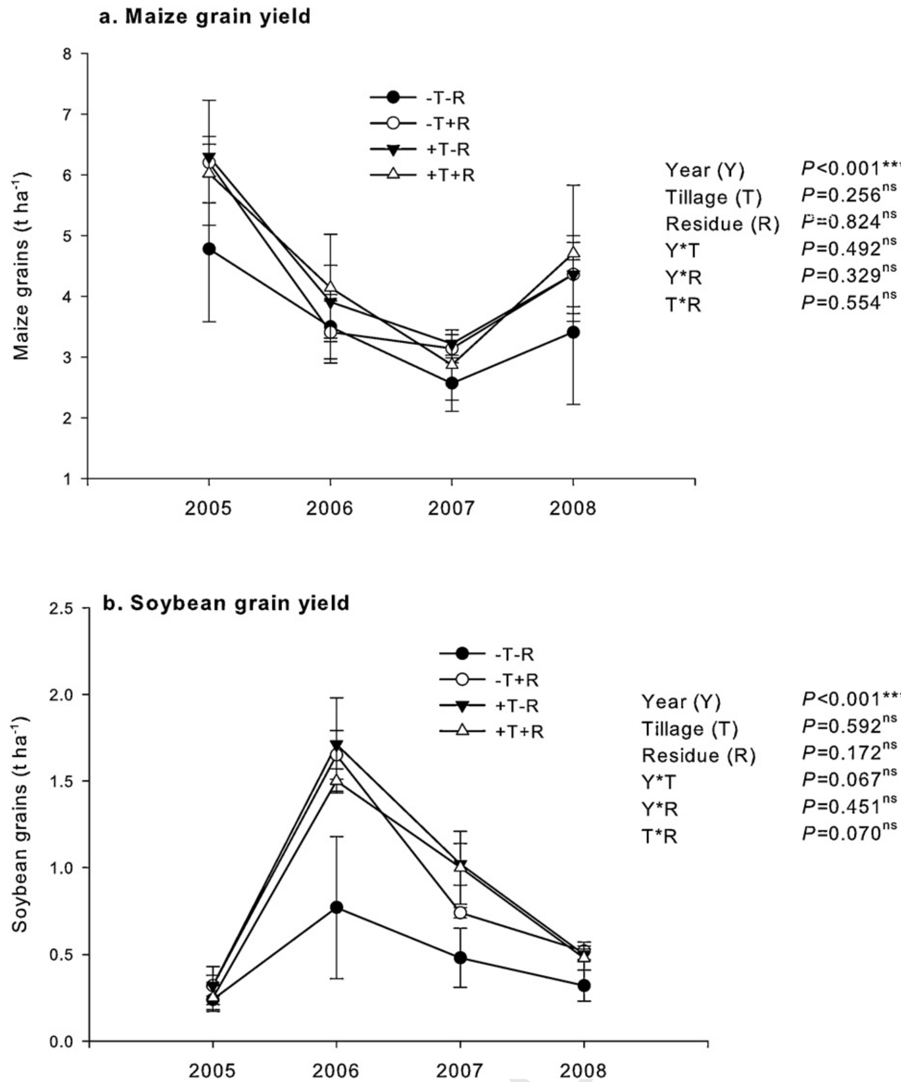

Fig. 4. Maize grain yields (a) and soybean grain yields (b) from 2005 to 2008. Codes refer to combinations of reduced tillage (−T), conventional tillage (+T), residue removal (−R) and residue retention (+R). Error bars indicate standard errors. Levels of significance indicate single and interactive effects of year (Y), tillage (T) and residue (R) on yield over all years. *P* values refer to the following levels of significance: *<0.05, **<0.01, ***<0.001, and ns not significant.

verified after a longer period. Our results indicate that multi-year data are more representative than single-year data when looking at soil aggregation.

4.2. Tillage and residue management effects on soil (aggregate) C

No significant management effects on total soil C content in the upper soil layer were found, even after 11 cropping seasons since trial establishment. It is peculiar that residue retention combined with mineral fertilizer did not have a beneficial impact on upper soil C as found in numerous other studies (Vanlauwe et al., 2001; Bationo et al., 2007; Chivenge et al., 2007, 2011; Anyanzwa et al., 2010). A possible explanation could be the low residue cover in the present study. The rate of 2 t ha^{-1} is however a realistic maximum rate attainable under smallholder farm conditions in sub-Saharan Africa, given the low biomass production and high competition for residue use (e.g. fodder) (Erenstein et al., 2008). A residue retention of 2 t ha^{-1} might not be sufficient to unfold potentially beneficial effects on soil C. Critical minimum amounts of residue retention required to improve soil C content and related soil properties has not yet been established and may depend on soil type and climatic conditions (Giller et al., 2011). Moreover, it is likely that the residue cover in the current study was further depleted by removal of crop residues by termites. At the same study site, Kihara (2009) observed that 85% of the residues retained at the soil surface disappeared within 3.5 months of application and that 70–95% of this was removed by macrofauna.

At 15–30 cm depth, conventional tillage combined with residue retention increased the soil C content in comparison to reduced tillage. As a consequence, we did not find an increase in soil C due to reduced tillage when considering the upper 30 cm of the soil, irrespective of residue management (Table 1). Recent literature shows that overall soil C stocks are often not enhanced under CA when considering the 0–30 cm soil layer or deeper, despite higher C contents in the upper centimeters of the soil (Gal et al., 2007; Govaerts et al., 2009; Luo et al., 2010).

Our results do not indicate that CA increases C protection in aggregate fractions. Although tillage increased C concentrations at 15–30 cm due to organic matter incorporation, this equally happened across LM, SM and Mi fractions without C accumulation in any specific aggregate fraction. The C contents of different aggregate fractions were also comparable. Moreover, despite the higher soil organic C content at 0–15 cm than at 15–30 cm soil depth (Table 1), aggregate stability was lower at 0–15 cm than at

15–30 cm (Fig. 3a and b). Other findings from Kenyan Ferrasols support this observation (Ayuke et al., 2011a). These results indicate that an aggregate hierarchy is not expressed. The aggregate hierarchy theory has been established for 2:1 clay dominated soils where SOM is the main binding agent. In these soils, C concentration increases with aggregate size, and aggregate stability is higher in surface soils with higher C contents. In 1:1 clay-dominated soils rich in Fe and Al oxides, electrostatic interactions decrease the correlation between SOM and aggregate stability (Oades and Waters, 1991; Denef and Six, 2005). This lack of correlation renders the expression of aggregate hierarchy less pronounced, and weakens the relationship between loss of soil structure and SOM (Elliott, 1986; Six et al., 2000). If CA is to be promoted among smallholder farmers in SSA for its C sequestration potential, we need to gain a better scientific understanding of C stabilization across different tropical 1:1 soils.

4.3. Tillage and residue management effects on maize and soybean yields

Tillage and residue management alone did not have a significant effect on maize or soybean yields over a time period of 8 cropping seasons (Fig. 4a and b). The high annual variation in crop yields due to variation in rainfall weakened the significance of main treatment effects. Numerous field studies reported increased yields from crop residue application in addition to mineral fertilizer (Palm et al., 2001; Vanlauwe et al., 2001; Anyanzwa et al., 2010), especially under reduced tillage (Govaerts et al., 2005). In our study, the total average soybean grain yield under reduced tillage without residue retention (–T–R) was 45% lower than under the other treatments. Other research from the sub-humid highlands of Kenya (Guto et al., 2011) and the semi-arid highlands of Mexico (Govaerts et al., 2005) also concluded that reduced tillage without soil cover cannot sustain high yields. In our study, the relative reduction in soybean yield was especially strong in 2006 (–53%), which was relatively wet season (846 mm rainfall) when compared to the other years studied (625–713 mm) (Fig. 1). Therefore high runoff resulting from soil crusting in –T–R treatments might have contributed to the lower soybean grain yield. This hypothesis is supported by Kihara (2009) who measured lower crop water productivity in –T–R than in –T+R in the same study site. Moreover, similar to Baudron et al. (2012), yields were not increased under reduced tillage with residue retention (–T+R). Such yield increases were found by other researchers in Southern and Eastern Africa (Rockström et al., 2009; Thierfelder and Wall, 2010). A possible explanation for the less distinctive positive effects of residue mulching on crop yields could be the semi-humid climate of our study area, where drought stress is restricted to certain years only and mostly in the short rainy season when soybean was grown.

5. Conclusions

Based on multi-year, quantitative data on the effects of tillage and residue management on soil aggregate stability, soil organic C and crop yields, we conclude that: (a) conventional tillage negatively affected soil aggregate stability when compared to reduced tillage, thus suggesting increased susceptibility to slaking and soil erosion. (b) Tillage and residue management alone did not affect soil C contents, but when residue was incorporated by tillage, soil C was higher at 15–30 cm. (c) Lack of treatment effects on the C content of different aggregate fractions indicated that reduced tillage and/or residue retention did not increase physical C protection. (d) The weak residue effect on aggregate stability and soil C may be attributed to insufficient residue retention. (e) Soybean grain yields tended to be suppressed under reduced tillage without residue retention, especially in wet seasons. Consequently, future research should establish, for different climatic zones and soil types, the critical minimum residue retention levels for soil conservation and crop productivity.

Uncited reference

Q2

Wood (1991).

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