Agriculture, Ecosystems and Environment 164 (2013) 14–22

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

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

B.K. Paul[a,*], B. Vanlauwe[b,1], F. Ayuke[a,b,2], A. Gassner[c], M. Hoogmoed[a,b,3], T.T. Hurisso[a,b,4], S. Koala[b], D. Lelei[b,d,5], T. Ndabamenye[a,b,6], J. Six[e], M.M. Pulleman[a]

[a] Wageningen University, Department of Soil Quality, P.O. Box 47, 6700AA Wageningen, The Netherlands
[b] CIAT-TSBF (International Center for Tropical Agriculture, Tropical Soil Biology and Fertility Research Area), P.O. Box 823-00621, Nairobi, Kenya
[c] ICRAF (World Agroforestry Center), Research Methods Group, P.O. Box 30677, 00100 Nairobi, Kenya
[d] University of Nairobi, Department of Land Resource Management and Agricultural Technology, P.O. Box 30197, 00100 Nairobi, Kenya
[e] University of California, Department of Plant Sciences, One Shields Ave, Davis, CA 95616, USA

ARTICLE INFO

Article history:
Received 6 February 2012
Received in revised form 9 October 2012
Accepted 16 October 2012
Available online 23 November 2012

Keywords:
Reduced tillage
Crop residue management
Soil aggregate stability
Crop yields
Soil organic carbon
Sub-Saharan Africa

ABSTRACT

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 ($P_{T*R} = 0.037$). 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;

* Corresponding author. Current address: CIAT (International Center for Tropical Agriculture), Tropical Forages Program, P.O. Box 823-00621, Nairobi, Kenya. Tel.: +254 20 863 2800; fax: +254 20 863 2001.
E-mail address: B.Paul@cgiar.org (B.K. Paul).
[1] Current address: IITA (International Institute of Tropical Agriculture), Natural Resource Management Research Area, P.O. Box 30772-00100, Nairobi, Kenya.
[2] Current address: University of Nairobi, Department of Land Resource Management and Agricultural Technology, P.O. Box 30197, 00100 Nairobi, Kenya.
[3] Current address: Monash University, School of Biological Sciences, Clayton, VIC 3800, Australia.
[4] Current address: University of Wyoming, Department of Renewable Resources, College of Agriculture and Natural Resources, Laramie, WY 82071-3354, USA.
[5] Current address: ICRAF (World Agroforestry Center), 00100 Nairobi, Kenya (in addition to Nairobi University).
[6] Current address: Rwanda Agriculture Board (RAB), Infrastructure and Mechanization Directorate, P.O. Box 5016 Kigali, Rwanda.

0167-8809/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agee.2012.10.003

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).