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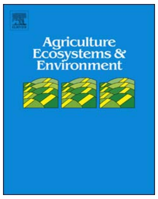

Research Paper

Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya

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ABSTRACT

Agriculture is a global contributor to greenhouse gas emissions, causing climate change. Soil organic carbon (SOC) sequestration is seen as a pathway to climate change mitigation. But, long-term data on the actual contribution of tropical soils to SOC sequestration are largely absent. To contribute to filling this knowledge gap, we measured SOC in the top 15 cm over 12 years in two agronomic long-term trials in Western Kenya. These trials include various levels – from absence to full adoption – of two widely promoted sustainable agricultural management practices: Integrated Soil Fertility Management (ISFM; i.e. improved varieties, mineral fertilizer and organic matter/manure incorporation) and Conservation Agriculture (CA; improved varieties, mineral fertilizer, zero-tillage and crop residues retention). None of the tested ISFM and CA treatments turned out successful in sequestering SOC long-term. Instead, SOC decreased significantly over time in the vast majority of treatments. Expressed as annual averages, losses ranged between 0.11 and 0.37 t C ha^{-1} yr^{-1} in the CA long-term trial and 0.21 and 0.96 t C ha^{-1} yr^{-1} in the ISFM long-term trial. Long-term application of mineral N and P fertilizer did not mitigate SOC losses in both trials. Adopting zero-tillage and residue retention alone (as part of CA) could avoid SOC losses of on average 0.13 t C ha^{-1} yr^{-1}, while this was 0.26 t C ha^{-1} yr^{-1} in response to mere inclusion of manure as part of ISFM. However, cross-site comparison disclosed that initial SOC levels of the two trials were different, probably as a result of varying land use history. Such initial soil status was responsible for the bulk of the SOC losses and less so the various tested agronomic management practices. This means, while ISFM and CA in the humid tropical agro-ecosystem of Western Kenya contribute to climate change mitigation by reducing SOC losses, they do not help offsetting anthropogenic greenhouse gas emissions elsewhere.

1. Introduction

Agriculture contributes 14 % to global anthropogenic greenhouse gas (GHG) emissions, and another 17 % through land use change, making it a major cause of climate change (Smith et al., 2008). Rather than being part of the problem, agriculture is sought to become part of the solution to climate change (OECD, 2016). Increasing carbon (C) stocks in agricultural landscapes as a means to mitigate climate change gained significant momentum in global debate with the last Conferences of the Parties (22) of the UNFCCC. At best, such carbon sequestration includes above- and below-ground sinks (Smith, 2016). As far as soils are concerned, the 4p1000 Initiative (http://4p1000.org/) set an aspirational target to increase global soil organic carbon (SOC) amounts in the top 40 cm of soils by 4‰ per year. According to the underlying rough estimates, the global effect of such sequestration would be enormous, with a proclaimed potential to halt any further increase of CO_2 concentration in the atmosphere (Lal, 2016). The discussion around C sequestration in soils ranges back at least 15 years. Ever since, the actual achievable net C sequestration effects have been contested (Stockmann et al., 2013; Powlson et al., 2011; Sommer and de Pauw, 2011; Baker et al., 2007; Lal, 2003). Sommer and Bossio (2014) argued it will take time to adopt measures to increase the SOC content of soils, i.e. realistically not all soils can be turned into SOC sinks immediately. Also, an increase in SOC does not proceed linearly for many years, but SOC sequestration in upland soils usually levels off at some point in time, e.g. after 20–30 years (West and Six, 2007). Both processes combined suggest it is flimsy to determine a fixed amount of SOC that could be sequestered on an annual basis for years to come at global scale. Irrespectively, there are numerous studies that present fixed annual quantities that could technically be sequestered. Most of them simply multiply per-area sequestration rates (e.g. t C ha^{-1} yr^{-1}) with estimated areas, as shown for several country case studies by

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Minasny et al. (2017). Other studies in addition exclude soils with supposedly less sequestration potential such as soils in arid environment, peatland and wetland soils, or distinguish between forest soils, agricultural soils and/or rangeland and agricultural soils (Minasny et al., 2017; Paustian et al., 2016; Wollenberg et al., 2016; Lal 2010, 2003; Smith et al., 2008). Calculated potentials of these studies range between mitigating around 5 to 15% (Smith et al., 2008; Paustian et al., 2004) up to fully offsetting anthropogenic emissions (4p1000).

Regardless of the exact amount of potential C sequestration, the underlying assumption is that there are viable management practices to turn soils into C-sinks. Conservation Agriculture (CA) and Integrated Soil Fertility Management (ISFM) are arguably the most well-known soil conserving techniques in the humid tropics of sub-Saharan Africa (SSA). They are said to sequester SOC if adopted in their entireness, but adoption numbers and acreage are lacking for SSA. ISFM refers to a judicious combination of mineral fertilizer and organic inputs together with improved germplasm and sound agronomy to reach higher crop productivity and resource use efficiency (Sanginga and Woomer, 2009). Although ISFM is argued to increase SOC (Bationo et al., 2007; Tittonell et al., 2007), long-term evidence is lacking. Conservation agriculture (CA) is built on three pillars – minimum soil disturbance (e.g. by zero-tillage), crop residue retention on the soil surface, and increased diversification through rotation and/or intercropping of different crop species (Hobbs et al., 2008). A number of studies have been measuring SOC under CA in the long-term. While clear sequestration benefits were observed in researcher-managed trials (Thierfelder et al., 2014; Verhulst et al., 2012), the signal was less clear in farmer's fields (Cheesman et al., 2016; Pittelkow et al., 2014; Powlson et al., 2014), and thus euphoria somewhat dampened at last (Powlson et al., 2016). Also, long-term data on the C-sink performance of CA systems in the humid tropics of Africa have not been presented so far.

This paper hence intends to deepen our understanding of SOC of humid tropical agro-ecosystems of SSA exposed to ISFM and CA management in the long-term. We present data from long-term trials in Western Kenya, a densely populated, intensive farming region of Kenya. New and historic soil samples were analysed to assess the impact of contrasting agricultural management practices on SOC dynamics and potentials for C-sequestration. The agronomic performance of the two trials will be published in a forthcoming paper, and therefore is not presented and discussed here.

2. Material and methods

2.1. Study area

Since 2003, the International Center for Tropical Agriculture (CIAT) maintains two long-term, researcher managed, on-farm trials in Kenya. The first trial, CT1, compares soil fertility and agronomic performance of conservation agriculture to conventional agriculture. The second trial, INM3, focuses on Integrated Soil Fertility Management (ISFM). Both trials are located in Western Kenya, 50 km northwest of the city of Kisumu. CT1 is at 0° 7′46.96″N, 34°24′19.15′E and INM3 at 34° 24′ 13.7′ E 00° 08′ 38.3″ N. They are 1.6 km apart at an altitude of 1330 m above sea level. The climate in the study area is sub-humid with a mean annual temperature of 22.5 °C and annual rainfall between 1200 and 2206 mm (average 1727 mm; observation period 1997–2013) distributed over two rainy seasons: the long rainy season lasts from March until July and the short rainy season from September until January. Maize (*Zea mays*) is the dominant staple crop in this region and is often grown in intercropping with food legumes such as common bean (*Phaseolus vulgaris*) or, more recently, soybean (*Glycine max*). The soils in the two sites are classified as Acric Ferralsols, with a clay content of between 56% (topsoil) and 84 % (subsoil; Table 1), low CEC and high aluminium saturation, a pH between 4.9 and 5.5, and a topsoil organic matter (SOM) content of between 30 and 45 g kg^{-1}. Major growth limiting nutrient are – in the order of importance – phosphate (P), nitrogen (N) and potassium (Kihara and Njoroge, 2013).

Table 1
Soil texture and bulk density of the soil profiles at INM3 and CT1 (Jelinski et al., unpublished); bulk density was measured taking undisturbed samples (n = 3 each) by driving 100 cm^3 steel rings horizontally into the mid of the respective layer using an Eijkelkamp open ring holder and plastic hammer.

Soil layer	Sand	Clay	Silt	BD
(cm)	——— (g 100 g^{-1}) ——-			(g cm^{-3})
INM3				
0−19	26	56	18	1.10
19–60	10	82	8	1.24
60–110	8	84	8	1.10
110–171	6	84	10	1.26
171–194	26	64	10	1.32
CT1				
0−8	24	58	18	1.09
8–40	14	72	14	1.11
40–91	10	82	8	1.17
91–168	12	80	8	1.09
168–195	12	76	12	n.d.

While soil erosion is common in the humid tropics including Western Kenya, the two CIAT long-term trials are located on almost perfectly flat land, and hence loss of topsoil in response intensive rainfalls and surface runoff is not a concern.

According to the owner of the field, INM3 had been under a grass-shrub fallow for an unknown length of time until 2003. Fallow species included the invasive, perennial shrub *Lantana camara.* At the beginning of 2003, the site was manually cleared by the farmer for conventional cultivation of maize without inputs of organic or mineral fertilizer for one year. CT1 had been under maize from 1992 to 1994 (unfertilized), then left fallow for 6 years, after which it was cultivated again with maize until 2004 (8 seasons), but this time with seasonal inputs of around 100 kg ha^{-1} di-ammonium phosphate fertilizer.

2.2. Experimental setup

Both long-term trials are laid out in a split-split–split plot design with four reps (blocks), 44 treatments and 192 plots in total. Each plot measures 4.5 m × 6 m. CT1 has two tillage systems – zero tillage (0T) and conventional tillage (CT) – as main plots, and two residue (R) levels as sub-plots, one on which 2 t ha^{-1} maize stovers are retained (R +) and the second one where all residues are removed after harvest (R-). Sub-sub-subplots are three cropping rotations, namely continuous maize (M-M), soybean-maize rotation (M-S or S-M) and continuous maize-soybean intercropping (MS). In the following, S-M indicates the rotation where soybean is grown in the long rainy season followed by maize in the short rainy season, while M-S denotes the inverse. INM3 has an analogous layout to CT1, but with a different focus. The first split encompasses plus (4 t dry matter per ha per season) or minus farm yard manure (FYM) application, and the second split factor addresses – as CT1 does – residue retention (2 t ha^{-1} maize stover retained vs. all stover removed). The third split factor comprises three crop rotations, continuous maize (M-M), Tephrosia–maize (T-M or M-T; notation analogous to S-M/M-S in CT1) rotation, and maize-soybean intercropping (MS). *Tephrosia* (family *Fabaceae*) is a legume genus that comprises more than 20 different perennial species. We used *Tephrosia candida*, which is one of the poisonous species of *Tephrosia* for its high concentration of rotenone, and which is common in the region and seeds easily available.

Plots of CT1 as well as INM3 received between 0 and 90 kg N ha^{-1} per season as urea and 0 or 60 kg P ha^{-1} per season as triple super phosphate, with individual levels aliased with the crop rotation treatments. All plots also received 60 kg potassium ha^{-1} per season in the form of muriate of potash. In INM3, phosphate, potassium and 1/3 of