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Exclusion of soil macrofauna did not affect soil quality but increased crop yields in a sub-humid tropical maize-based system

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ABSTRACT

Soil macrofauna such as earthworms and termites are involved in key ecosystem functions and thus considered important for sustainable intensification of crop production. However, their contribution to tropical soil quality and crop performance, as well as relations with agricultural management (e.g., Conservation Agriculture), are not well understood. This study aimed to quantify soil macrofauna and its impact on soil aggregation, soil carbon and crop yields in a maize–soybean system under tropical sub-humid conditions. A field trial was established in Western Kenya in 2003 with tillage and residue retention as independent factors. A macrofauna exclusion experiment was superimposed in 2005 through regular insecticide applications, and measurements were taken from 2005 to 2012. Termites were the most abundant macrofauna group comprising 61% of total macrofauna numbers followed by ants (20%), while few earthworms were present (5%). Insecticide application significantly reduced termites (by 86 and 62%) and earthworms (by 100 and 88%) at 0–15 and 15–30 cm soil depth respectively. Termite diversity was low, with all species belonging to the family of Macrotermitinae which feed on wood, leaf litter and dead/dry grass. Seven years of macrofauna exclusion did not affect soil aggregation or carbon contents, which might be explained by the low residue retention and the nesting and feeding behavior of the dominant termites present. Macrofauna exclusion resulted in 34% higher maize grain yield and 22% higher soybean grain yield, indicating that pest damage – probably including termites – overruled any potentially beneficial impact of soil macrofauna. Results contrast with previous studies on the effects of termites on plant growth, which were mostly conducted in (semi-) arid regions. Future research should contribute to sustainable management strategies that reduce detrimental impact due to dominance of potential pest species while conserving soil macrofauna diversity and their beneficial functions in agroecosystems.

1. Introduction

Feeding a rapidly growing human population while preserving environmental sustainability results in unprecedented challenges for agriculture and natural resources. Sustainable intensification is especially urgent in Sub-Saharan Africa where soil degradation and food insecurity are most pressing, and smallholder farmers are challenged by scarcity of resources including organic and inorganic fertilizers (Godfray et al., 2010; Garnett et al., 2013). It is of crucial importance that management of agricultural soils enhances and sustains soil fertility and resource use efficiency, based on a better understanding of ecosystem services (Beare et al., 1997; Brussaard et al., 2010). Management practices involving minimum soil disturbance, organic soil cover and crop diversification – collectively

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known as Conservation Agriculture (CA) – are widely promoted in Sub-Saharan Africa. CA has been shown to stimulate soil macrofauna, which, in turn, can lead to enhanced soil aggregation and therefore C storage, reduced runoff and erosion, improved nutrient and water use efficiency, and ultimately stable crop yields. These potential impacts however vary with specific agro-ecologies (Erenstein, 2003; Hobbs, 2007; Palm et al., 2014; Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014).

A wide range of different soil macrofauna provides ecosystem services including soil organic matter turnover, nutrient cycling, soil structure formation and pest and disease control (Lavelle et al., 1997; Beare et al., 1997; Brussaard, 2012). Of key interest are soil ecosystem engineers such as earthworms, termites and, to a lesser extent ants. Through bioturbation they incorporate plant litter and crop residues into the soil, thereby modifying biological, chemical and physical soil processes that affect the flow of energy and material, and modify the habitat of other soil biota (Jones et al., 1994; Lavelle et al., 1997; Pulleman et al., 2012). The impact of soil ecosystem engineers on soil quality is partly mediated through their effects on soil organic matter incorporation and soil aggregation (Six et al., 2004). Stable soil aggregates can physically protect soil organic matter against rapid decomposition (Six et al., 2000) and reduce soil erosion (Barthes and Roose, 2002). It has been shown that the biogenic structures produced by earthworms and termites, such as casts and sheetings, can differ from bulk soil in organo-physical composition and tend to be enriched in carbon and nutrients, suggesting protection of organic matter against rapid mineralization (Fall et al., 2001; Mora et al., 2003; Pulleman et al., 2005; Bossuyt et al., 2005). The capacity of earthworms to incorporate organic matter into the soil and improve soil aggregation has been widely investigated (Lee, 1985; Lavelle et al., 1997; Six et al., 2004), although effects on C mineralization versus C stabilization are still a matter of debate (Lubbers et al., 2013). It has also been shown that earthworm abundance is generally higher in no-tillage systems due to the lack of mechanical soil disturbance (Chan, 2001; Shuster and Edwards, 2003; Castellanos-Navarrete et al., 2012).

Termites are considered the dominant soil ecosystem engineers in tropical (semi)-arid areas, whereas earthworms occur widely in (semi-) humid climates, both tropical and temperate (Lal, 1988; Lobry de Bruyn and Conacher, 1990). Termites are well known for their role in organic matter breakdown and modification of soil properties. They construct a variety of organo-mineral structures that result from intestinal transit (casts) or are mixed and impregnated with saliva and are used to construct mounds, nests, galleries and surface sheetings (Lobry de Bruyn and Conacher, 1990; Fall et al., 2001; Mora et al., 2003). Termites can mold up to 1300 kg ha^{-1} of soil annually (Kooyman and Onck, 1987) and it has been suggested that their biogenic structures constitute microsites that protect organic C against rapid mineralization (Mora et al., 2003). Termites are classified on the basis of their food choice, feeding habits and nesting behavior, ranging from soil feeders that occur in the soil profile and feed on organic matter associated with mineral soil, wood feeders that feed on wood and excavate galleries in larger items of wood litter, and litter feeders that forage for leaf litter, dry standing grass stems and small woody items (Swift and Bignell, 2001; Eggleton and Bignell, 1995; Wood, 1996). Similarly, ants modify the soil through foraging and nest building although their impact on soil properties is generally less important compared with earthworms and termites (Jungerius et al., 1999; Lobry de Bruyn and Conacher, 1990).

A number of studies focusing on natural Savanna ecosystems in Australia and West Africa have reported beneficial effect of termites on soil porosity, water infiltration, nutrient uptake and plant cover or biomass, demonstrating their capacity to rehabilitate degraded and crusted soils (Sarr et al., 2001; Dawes, 2010; Mando and Brussaard, 1999). In Kenya, the role of termites and ants in the formation of the microgranular structure of Ferralsols was studied by Jungerius et al. (1999), whereas Fall et al. (2001) compared the effects of different termite feeding groups on soil organic matter and aggregate fractions in West African semi-arid Savanna. Few studies exist, however, that have evaluated the effects of termites or ants on agricultural soils (Kooyman and Onck, 1987; Lobry de Bruyn and Conacher, 1990; Evans et al., 2011), as research on termites in agricultural systems has historically focused on their pest role (Wood and Cowie, 1988; Black and Okwakol, 1997; Bignell, 2006). Positive effects of tropical soil macrofauna on crop yields have been demonstrated experimentally in a limited number of studies, again in (semi-) arid climates in West Africa (Ouedraogo et al., 2006, 2007) and West Australia (Evans et al., 2011), where low rainfall and poor surface structure strongly constrain crop production. The impact of soil macrofauna on soil structural properties, soil C and crop performance in (sub) humid climates, as well as their response to soil tillage and crop residue management in CA systems is largely unclear (Giller et al., 2009).

The overall aim of our study was to quantify the contribution of soil macrofauna (earthworms, termites, and ants) to soil aggregation, soil C and crop productivity as a function of different tillage and residue management under sub-humid climatic conditions. The hypotheses tested were:

(i) Soil tillage and residue removal negatively affect the abundance of soil macrofauna;
(ii) Soil macrofauna increase stable soil aggregation and soil C;
(iii) Soil macrofauna increase crop yields through positive effects on soil quality.

2. Materials and methods

2.1. Site description

This study was conducted in an existing long-term conservation tillage trial in Nyabeda, Siaya district, Nyanza province in Western Kenya. The site is located at an altitude of 1420 m asl, latitude 0° 06′N and longitude 34° 24′E, and the slope is less than 2%. A mean annual rainfall of 1800 mm (sub-humid) is distributed over two rainy seasons: the long rainy season lasts from March until August and the short rainy season from September until January (Fig. 1). The soil was identified as a Ferralsol (FAO, 1998) with five distinctive soil horizons. The upper soil horizon (0–8 cm) had 58% clay, 24% sand, and 18% silt. Soil chemical characteristics of the same soil layer included pH (H_2O) 5.1, total N 0.16%, total C 2%, Bray P 8 ppm, Olsen P 8.1 mg kg^{-1}. The second soil horizon (9–40 cm) had 72% clay, 14% sand, 14% silt, and pH (H_2O) 5.6, total N 0.15%, total C 1.6%, Bray P 1 ppm, Olsen P 2.7 mg kg^{-1} (Nic Jelinski, 2014, unpublished data).

2.2. Experimental design and trial management

The field experiment was established in March 2003, and has been managed by researchers and technicians of the International Center for Tropical Agriculture (CIAT). The trial was set up in a randomized block design ($n = 4$) 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). Individual plots measured 7 × 4.5 m. The crop rotation since trial establishment has consisted of soybean (*Glycine max* L.) during short rains and maize (*Zea mays* L.) during long rains. All plots were fertilized with 60 kg ha^{-1} N (urea), 60 kg ha^{-1} P (Triple Super Phosphate) and 60 kg ha^{-1} K (Muriate of Potash) per