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Integrated Soil Fertility Management: Aggregate carbon and nitrogen stabilization in differently textured tropical soils

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ABSTRACT

Soil organic matter is important to improve and sustain soil fertility in tropical agroecosystems. The combined use of organic residue and fertilizer inputs is advocated for its positive effects on short-term nutrient supply, but the effect of the integrated use on long-term stabilization of soil organic C and N is still unclear. We conducted a 1.5-y soil incubation experiment with maize (*Zea mays*) residue and urea fertilizer to examine the stabilization of C and N in four Sub-Saharan African soils differing in texture (sand, sandy loam, clay loam, and clay). The inputs were enriched with ^{13}C and ^{15}N in a mirror-labelling design to trace the fate of residue-C and N, and fertilizer-N in combination. We hypothesized that combining inputs would enhance the stabilization of C and N relative to either input alone across a range of soil textures. The treatments were destructively sampled after 0.25, 0.5, and 1.5 y to assess input-derived C and N stabilization in soil macro- and microaggregate fractions. The combination treatment had a significant but small (2% of residue-applied C) increase in residue-C stabilized in the total soil after 0.25 y, but this increase did not persist after 0.5 and 1.5 y. While combining residue and fertilizer decreased the amount of residue-N stabilized within 53- to 2000-μm sized soil aggregates (e.g., 7% less at 1.5 y), it increased the stabilization of fertilizer-N at all sampling times (e.g., 20% more at 1.5 y). The increased amount of fertilizer-N stabilized was significantly greater than the amount of residue-N lost in the combined input treatments in the three finer textured soils at 1.5 y, indicating an interactive increase in the stabilization of new N. Our results indicate that combining residue with fertilizer inputs can increase the short-term stabilization of N, which has the potential to improve soil fertility. However, benefits to N stabilization from combining organic residues and fertilizer seem to be less in coarser-textured soils.

1. Introduction

Concern about the long-term sustainability of tropical agroecosystems has generated much research on soil organic matter (SOM) formation, preservation and function in recent decades. Soil organic matter plays a fundamental role in soil nutrient dynamics, water retention, erosion prevention, biological activity, and greenhouse gas balances. The preservation of SOM for nutrient supply is especially pertinent for Sub-Saharan Africa where soil fertility decline is considered the most important constraint to crop production (Sanchez and Jama, 2002). Smallholder farmers, highly weathered soils, and low fertilizer inputs characterize agroecosystems in this region. Integrated Soil Fertility Management (ISFM) is a research and outreach paradigm currently advocated in Sub-Saharan Africa. It is an approach to optimize the application of all available resources in adaptation to local conditions to maximize nutrient use efficiency and crop productivity (Vanlauwe et al., 2010). The combined use of mineral fertilizer and organic residue inputs is one of the pillars of ISFM. This recommendation stems from the practical limitation that often neither input is available or affordable in sufficient quantities or qualities to be used alone. Furthermore, the combination of the two resource types may also benefit agroecosystem functioning through interactive effects leading to synchrony of available soil N supply and crop N demand, reduction of N losses, and the stabilization of SOM (Vanlauwe et al., 2001; Gentile et al., 2011).

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Table 1
Initial physical and chemical characteristics of four soils incubated with different input treatments.

Soil	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	WHC (%)	MWD (mm)	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Mineral N ($mg\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	pH (1:1 water)
Sand	890	63	48	21	0.76	2.5	0.16	4.9	0.71	5.39
Sandy loam	751	48	200	30	0.89	5.2	0.36	9.0	1.95	5.49
Clay loam	376	333	291	42	2.07	22.6	2.20	89.2	7.32	4.42
Clay	28	219	753	63	1.12	29.4	2.66	35.4	16.03	5.43

WHC, water holding capacity; MWD, aggregate mean weight diameter; CEC, cation exchange capacity.

Beneficial interactive effects of combining fertilizer and residue inputs are, for example, possible through short-term changes in N dynamics (Vanlauwe et al., 2001). The temporary immobilization of fertilizer-N due to increased microbial activity induced by the addition of residue as an available C source, can reduce initial N loss of fertilizer-N, whereas the subsequent stimulation of residue decomposition due to a readily available N supply by the fertilizer can increase the release of residue-N. These combined processes may improve N synchrony between soil supply and plant demand, compared with the use of fertilizer or residue inputs alone, especially when the residue is of a low quality, characterized by a slow rate of mineralization. Maize stover is classified as a low quality residue and is one of the most widely available organic residues in Sub-Saharan Africa (Palm et al., 2001; Vanlauwe et al., 2006). Incorporating maize (*Zea mays*) residue with N fertilizer has been found to reduce leaching of fertilizer-N (Vanlauwe et al., 2002), reduce N_2O fluxes in coarse-textured soils (Gentile et al., 2008), and improve crop N uptake (Gentile et al., 2011).

While there is evidence for beneficial short-term interactions of combining fertilizer and residue inputs, the implications for SOM stabilization are still unknown. Soil aggregates are the units in which SOM is physically protected in the soil (Oades, 1984; Elliott, 1986); therefore, their structure and dynamics can play an important role in controlling C and N stabilization. The conceptual model of aggregate turnover by Six et al. (2000) describes the decomposition of plant residues into more stable compounds as they are incorporated into aggregates and organomineral complexes. Recently added organic material becomes a nucleus for stable macroaggregate formation, and with subsequent decomposition it forms microaggregates within the macroaggregates (Golchin et al., 1994; Six et al., 1999). Macroaggregate dynamics control SOM stabilization, as microaggregates formed within macroaggregates have been found to be the structures in which C and N are preferentially stabilized in both temperate and tropical soils (Denef et al., 2004; Kong et al., 2005). An intermediate rate of macroaggregate turnover is proposed to result in maximum stabilization of SOM, as it is slow enough to allow for microaggregate formation, but fast enough to occlude and protect newly added residues (Plante and McGill, 2002). Since N fertilizer has been found to increase the rate of aggregate formation and breakdown (Harris et al., 1963), we hypothesized that combining fertilizer and maize residue inputs will result in an intermediate rate of aggregate turnover that is optimal for C and N stabilization.

Soil texture has been shown to be a major controlling factor on whole soil and fraction SOM stabilization (Feller and Beare, 1997; Plante et al., 2006). In general, soil C and N stabilization increases with increasing clay content because of the greater reactive surface area of clay particles increasing the soil's capacity to stabilize SOM chemically (Feller and Beare, 1997; Hassink, 1997). Additionally, the greater surface area of fine-textured soil will lead to a greater aggregate quantity and a decreased susceptibility to disruptive forces (Kemper and Koch, 1966), thereby leading to a greater capacity to stabilize SOM physically. Therefore, fine-textured soils may predominantly form more aggregates with greater stability after residue inputs, leading to a greater protection of C and N than in coarse-textured soils. Kölbl and Kögel-Knabner (2004), in fact, found that clay content increased soil C in occluded particulate organic matter fractions.

The objectives of this study were to examine soil aggregate stabilization of C and N derived from residue and fertilizer inputs, when applied alone and in combination, across a soil texture gradient. We hypothesized that combining maize residue and fertilizer inputs would enhance the stabilization of C and N relative to either input alone across a range of soil textures. Additionally, we predicted that the interactive effect of combining input types would increase with increasing clay content.

2. Material and methods

2.1. Soils

Four soils from different agroecozones in Sub-Saharan Africa representing a range of soil textures were used in the experiment. These soils were a sandy soil (Ferralic Arenosol) from Makoholi, Zimbabwe; a sandy loam soil (Haplic Lixisol) from Domboshawa, Zimbabwe; a clay loam soil (Ferric Acrisol) from Kwadaso, Ghana; and a clay soil (Humic Nitisol) from Embu, Kenya (FAO, 1998). The sandy and sandy loam soils were from the dry savannah agroecozone in southern Africa with mean annual precipitation (MAP) of 660 mm and 800 mm, respectively, and a mean annual temperature (MAT) of 24 °C. The clay loam soil was from the humid forest agroecozone in western Africa with a MAP of 1480 mm and a MAT of 26 °C, and the clay soil was from the moist savannah agroecozone in eastern Africa with a MAP of 1200 mm and a MAT of 20 °C. Each site has been under cultivation for many years; therefore, the soils were assumed to be in steady state.

At each site, soils were collected from the 0–15 cm depth because this is the soil depth disturbed by hand cultivation at these sites. The soils were sieved through an 8-mm sieve, air-dried, and stored at room temperature until the initiation of the experiment. Initial soil physical and chemical characteristics are shown in Table 1.

2.2. Plant residues

Maize was grown in a greenhouse in a 3:1 sand:vermiculite mixture and was enriched in ^{13}C and ^{15}N according to the methods of Bird et al. (2003). Briefly, plants were pulse-labelled with $^{13}CO_2$ gas in a Plexiglas chamber over one photoperiod approximately every 7 days. Plants were watered and fertilized as needed with deionized water and a modified Hoagland's solution. One third of the plants received a fertilizer solution with unenriched ^{15}N (0.37 atom%), while the remaining plants were fertilized with a solution enriched in ^{15}N (60 atom%). The plants were harvested at flowering, chopped into 5-cm segments, and oven-dried at 40 °C. After drying, residues were cut into 2–8-mm sized pieces. Subsamples of each residue type were ground and subsequently analyzed for total C, total N and ^{13}C and ^{15}N isotopic signatures with a PDZ