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Nutrient availability limits carbon sequestration in arable soils

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ABSTRACT

Soils are the largest reservoir of global terrestrial carbon (C). Conversion from natural to agricultural ecosystems has generally resulted in a significant loss of soil organic-C (SOC, up to 50% or ~30–40 t ha $^{-1}$) and 'restoring' this lost C is a significant global challenge. The most stable component of soil organic matter (SOM), hereafter referred to as fine fraction SOM (FF-SOM), contains not only C, hydrogen (H) and oxygen (O), but substantial amounts of nitrogen (N), phosphorus (P) and sulphur (S), in approximately constant ratios. The availability of these associated nutrients is essential for the formation of FF-SOM. Here we show, in short term (56 day) incubation experiments with ^{13}C labelled wheaten straw added to four soils with differing clay content, that conversion of straw into "new" FF-SOM is increased by up to three-fold by augmenting the residues with supplementary nutrients. We also show that the loss of "old" pre-existing FF-SOM increased with straw addition, compared to soils with no straw addition, but that this loss was ameliorated by nutrient addition in two of our soils. This finding may illuminate why the build-up of SOC in some productive agricultural soils is often much less than expected from the amounts of C-rich residues returned to them because optimum C sequestration requires additional nutrients above that required for crop production alone. Moreover, it provides greater understanding of short-term dynamics of C turnover in soil, and in the longer term, may have important implications for global strategies aimed at increasing soil C sequestration to restore fertility and help mitigate climate change.

1. Introduction

Six elements, C, N, P and S, along with H and O, contribute 97% or more of the fresh weight of a wide range of organisms (Morowitz, 1968). As a consequence the biogeochemical cycles of C, N, P and S are often tightly linked (Mackenzie and Lerman, 1993). Redfield (1958) showed that the C:N:P atomic ratios of marine particulate organic matter (OM), primarily phytoplankton, were approximately constant and equal to the ratios of the dissolved nutrients in the ocean. Thus, treating the phytoplankton as essentially one single pool of living OM interacting with its oceanic environment has proved extremely useful to understand the ocean's biogeochemistry (Cooper et al., 1996; Field et al., 1998). We suggest a similar approach may prove useful in understanding the biogeochemistry of soil.

SOM affects many important soil properties. Although fresh plant residues are the primary raw materials for SOM formation, we define SOM throughout this paper as the organic fraction of the soil exclusive of the coarse fraction (CF) organic material composed of un-decayed plant and animal residues (SSSA, 2008). Magid and Kjaergaard (2001) showed that CF material (CF > 0.4 mm) was synonymous with light fraction organic material (LF < 1.4 g cm^{-3}) with regards to the amounts of C and N as well as physical appearance. This CF is often recognised as highly labile material with fast breakdown rates in soil (Golchin et al., 1994; Wander, 2004; Crow et al., 2007). In contrast, fine fraction SOM (FF-SOM <0.4 mm; synonymous with heavy fraction SOM >1.4 g cm^{-3}) is considered to be a more stabilised and slowly decomposing pool of SOM (Golchin et al., 1994; Magid and Kjaergaard, 2001). After removal of the CF, it was the remaining FF-SOM that Kirkby et al. (2011) showed had near constant C:N:P:S ratios. In this study we use FF-C to estimate this SOM pool. The FF-SOM accounts for 70–80% of the organic material in soils (Stevenson, 1994; Kogel-Knaber, 2002) while most of the remainder is partially degraded, but still recognisable, plant residues (CF). Repairing the world's degraded soils requires the adoption of management practices that increase the size of the FF-SOM pool in soil, thereby improving fertility and helping mitigate climate change by removing atmospheric carbon dioxide and storing it as more stabilised SOM.

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A common expectation in conservation agriculture, where soil is not ploughed and crop residues are retained rather than burnt or removed, is that SOC levels should substantially increase. However, several studies over long periods have shown that increased residue inputs have resulted in little, if any, increase in SOC (Campbell et al., 1991; Soon, 1998; Rumpel, 2008). In addition, it is now recognised that the addition of fresh organic material can increase the mineralisation of "old" OM already in the soil by a phenomenon known as the "priming effect" (PE) (Bingeman et al., 1953), leading to even greater SOC losses. Fontaine et al. (2004) showed that this PE could be of sufficient magnitude that the loss of "old" SOM exceeded the formation of "new" SOM, through humification of the freshly added organic material, leading to a net loss of SOC overall. It is now recognised that the PE can either retard or increase "old" SOM mineralisation. When the addition of fresh-C substrates increases the mineralisation of "old" SOM the phenomenon is referred to as a "positive PE" but when it retards the mineralisation of the "old" SOM it is referred to as a "negative PE". The activation of microorganisms by easily available substrates is generally considered to be the main reason for the occurrence of positive PE's in soil (Kuzyakov et al., 2000). While Kuzyakov and Bol (2006) and Hamer and Marschner (2002) suggest that microorganisms having r-strategy (organisms with a short lifespan but able to reproduce rapidly under favourable conditions, e.g. when food becomes available) were mainly responsible for the positive PE's they observed, there is no general agreement on this.

Because crop residues, such as wheaten straw, are C-rich but nutrient (N, P, S) poor, we hypothesised that supplementing a soil–straw mix with these nutrients would result in a greater proportion of straw-C being transformed into new FF-C, i.e. the humification efficiency (HE) would increase, than with straw alone. The nutrient ratios in FF-SOM are similar to those of soil microorganisms and this similarity supports the growing body of evidence that a large proportion of FF-SOM originates from microbial detritus, rather than directly from recalcitrant plant material (e.g. Kramer et al., 2003; Sollins et al., 2006; Lehmann et al., 2007; Liang, 2008; Bol et al., 2009; Miltner et al., 2009; Liang and Balser, 2011). The impact of added nutrients on microbial growth and turnover is therefore the likely key to increasing the conversion of C-rich residues to FF-SOM. Further, we hypothesised that using ^{13}C-enriched straw would allow us to track the transformation of added straw-C into "new" FF-C independent of any loss of pre-existing "old" FF-C. We did so because FF-SOM continually turns over, albeit slowly, and the common observation that SOC failed to build up in soils receiving large C inputs (Campbell et al., 1991; Soon, 1998; Rumpel, 2008) may be due to faster decomposition of "old" pre-existing FF-SOM (Kuzyakov et al., 2000) rather than no, or low, conversion of straw-C into "new" FF-C. In this paper we investigate the role of inorganic nutrients (N, P and S) in short-term C dynamics in soil by measuring both the amount of "new" FF-SOM formed by humification and the amount of "old" FF-SOM lost by decomposition when wheaten straw was added to a range of arable soils.

2. Materials and methods

We incubated four diverse soils in laboratory microcosms with and without straw and supplementary inorganic N, P and S and followed the changes in size of the pre-existing and newly formed FF-SOM pools. The added nutrients, equivalent to 5 kg N, 2 kg P and 1.4 kg S per tonne of straw, were designed to augment the nutrients within the straw to achieve the ratios of C:N:P:S found in FF-SOM (Table 1; Kirkby et al., 2013). In all experiments any partially decomposed plant residue (CF) was removed from the soils both before the experiment began and after the incubation with straw using a dry-sieving/winnowing procedure (Kirkby et al., 2011) such that any C remaining in the soil was assumed to be FF-C. In this way only changes in the more stable FF-SOM pool were assessed (Kirkby et al., 2011).

Table 1
Mass of N, P and S per 10,000 units C for some common crop residues, bacteria, fungi and fine fraction-SOM (Kirkby, 2011).

	C	N	P	S
Wheat straw	10,000	152	23	37
Maize stover	10,000	225	29	32
Rice straw	10,000	158	19	18
Bacteria	10,000	2504	494	264
Fungi	10,000	1034	110	94
FF-SOM	10,000	893	187	143

2.1. Characterisation of the initial soil

Surface soil samples (0–15 cm) were collected from four diverse agricultural soils (clay range 8–60%; starting FF-C range 0.6–3%, Table 2) representative of different agro-ecological regions of Australia. All CF organic material was removed as described above. The difference between the total-OC and FF-C values in Table 2, particularly for soils 1 and 4, indicates the level of partially degraded plant remains in some soils and indicates why it is so important to remove this material when studying FF-C dynamics. More detailed information regarding the soils can be found in Kirkby et al. (2013). Note that soil 1 (Buntine) is a Tenosol (Table 2) which was previously reported as a Kandosol in Kirkby et al. (2013).

2.2. Incubation experiment

Uniformly-stable isotope-labelled mature wheat stem (internode) > 97 atom% ^{13}C, was used as the enriched material (IsoLife Wageningen, Netherlands). This highly-enriched material was diluted (1:25; final atom% ^{13}C = 4.940) with non-labelled wheat stem (internode) material collected at harvest from Site 2 which had been oven dried (70 °C) and stored. Only internode stem material was used to maximise the uniformity of the material added to each replicate (Kirkby et al., 2013). The straw was cut into pieces approximately 5 mm long prior to mixing with any soil.

2.3. Treatments

There were three treatments in the experiment: (soil alone, the control), (soil + straw), (soil + straw + supplementary nutrients). All weights were to 0.1 mg accuracy and the initial atom% ^{13}C was calculated for each replicate based on the soil weight and the weights of the labelled and non-labelled straw added.

Table 2
Initial total organic-C and FF-C (mg kg^{-1} soil), atom% ^{13}C of the FF-C and other selected properties of the four soils used for the incubation experiment.

Soil	Buntine (1)	Harden (2)	Hamilton (3)	Leeton (4)
Soil group	Tenosol	Kandosol	Chromosol	Vertosol
Texture	Sand	Sandy loam	Sandy clay loam	Clay loam
Clay (%)	8	15	25	60
pH	4.80	5.29	5.15	5.84
Total-organic C	12,071	10,815	31,633	24,284
FF-C	6903	10,620	30,790	12,860
^{13}C atom% of FF-C	1.082	1.083	1.081	1.084