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Carbon and nutrient mineralisation dynamics in aggregate-size classes from different tillage systems after input of canola and wheat residues

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ABSTRACT

Aggregate-size classes may have different microbial accessibility and therefore different decomposability of aggregate-associated soil organic matter (SOM). However, processes and mechanisms of soil organic carbon (SOC) mineralisation and availability of nutrients [nitrogen (N), phosphorus (P) and sulphur (S)] in different aggregate-size classes, and particularly, the interaction of aggregates with tillage intensity and crop residue type in contrasting soils is poorly understood. Soil samples from conventional tillage (CT) and reduced tillage (RT) systems under mixed wheat–pasture farming, and no-till (NT) under continuous cereal–cover cropping in a Luvisol, and from CT and NT under continuous wheat cropping in a Vertisol, were separated into three dry aggregate classes of different sizes [mega-aggregates (> 2–6.5 mm), macro-aggregates (0.25–2 mm) and micro-aggregates (< 0.25 mm)]. Two residue types (canola and wheat stem; δ^{13}C 124 and 460‰, respectively) were added into each of the three aggregate class samples from Luvisol (δ^{13}C −24.7‰) and Vertisol (δ^{13}C −18.5‰). Total CO_2-C, δ^{13}C in CO_2-C, microbial biomass C (MBC), and plant available N, P and S were measured periodically during the 126-day incubation. The results showed that crop residue input increased native SOC mineralisation (*via* positive priming), MBC and microbial metabolic quotient in all three aggregate-size classes from different tillage systems in both soils. Native SOC mineralisation was 1.5–3.7 and 0.6–2.8 times higher in the canola and wheat residue-amended (*cf*. control, non-amended) aggregates, respectively. Native SOC mineralisatiion and MBC were higher in the macro- and micro- than mega-aggregates in both soils. However, priming of native SOC mineralisation, relative to the control, was similar across the aggregates, except for the CT in the Luvisol where priming was higher in the macro- than micro- and mega-aggregates. Native SOC mineralisation among the aggregate-size classes was 26–114% higher under CT or RT *cf*. NT in the Luvisol but was similar under CT and NT in the Vertisol. Net available N was significantly higher in the residue-amended than the control aggregates, particularly in the CT and/or RT *versus* the NT at day 30 only, and mainly in the Luvisol. Further, substantial amounts of available P and S were released from the residue-amended *versus* the control aggregates at day 126, with Vertisol releasing 2–3 times more available P than Luvisol. In conclusion, our findings showed the importance of returning crop residues to enhance nutrient availability from all aggregate-size classes in different soils and farming systems. In particular, the tillage (*versus* no-till) and canola (*versus* wheat) residue induced a greater release of nutrients, generally in the pattern of micro- ≥ macro- > mega-aggregates. Clearly, the input of crop residues enhanced the release of SOM-bound nutrients, possibly *via* positive priming, and may have mobilised mineral-bound nutrients, such as P and S in each aggregate-size class, with tillage intensity and soil type modulating these processes.

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1. Introduction

Soil structure and soil organic matter (SOM) are the two most dynamic soil properties, and are highly sensitive to agricultural management practices (Devine et al., 2014). Soil structure relates to arrangement of soil particles into units called aggregates, which are commonly grouped into different size classes [mega-aggregates (> 2 mm), macro-aggregates (0.25–2 mm) and micro-aggregates (< 0.25 mm)], with different stabilities (Six et al., 2000; Devine et al., 2014). Each aggregate-size class has been reported to contain SOM with different levels of physical protection and chemical composition, influenced further by management practices, and thus can contribute in different ways to the regulation of soil organic carbon (SOC) and nutrient mineralisation dynamics in agro-ecosystems (Tisdall and Oades, 1982; Six et al., 1998, 2002; Von Lützow et al., 2007).

In general, organic matter associated with micro-aggregates comprises well decomposed plant and microbial residues, that bind together with primary mineral particles *via* cation bridging, thus protecting SOM against microbial mineralisation (Six et al., 2002; Denef et al., 2007; Rabbi et al., 2014; Lehmann and Kleber, 2015). Further, fresh plant and microbial residues may also assist in binding clay particles and micro-aggregates into macro-aggregates and mega-aggregates, thus preserving partially decaying plant residues and microbial products within the aggregates (Six et al., 2002). However, coarser aggregates tend to have low structural stability, and hence are more sensitive to tillage than finer aggregates (Six et al., 1998, 2002). Further, any organic matter, less than 2 mm (which is classified as SOM) that may still be unprotected around macro-aggregates (*e.g.* free particulate organic matter; fPOM) or occluded within macro-aggregates and when exposed through tillage, would be more prone to microbial decomposition than that associated with, or protected within, micro-aggregates (Six et al., 1999).

There have been a few studies on the understanding of SOC mineralisation in aggregate classes of different sizes under different tillage intensity systems (Fernandez et al., 2010; Jacobs et al., 2010). In general, macro-aggregates with greater microbial accessibility and degradability of SOM showed higher SOC mineralisation than micro-aggregates (Six et al., 2000; Fernandez et al., 2010; Bimüller et al., 2016; Cai et al., 2016). In contrast, Rabbi et al. (2014) found no difference in SOC mineralisation from macro-*versus* micro-aggregates, while other studies found greater CO_2-C production from micro-*versus* macro-aggregates (Bossuyt et al., 2002; Drury et al., 2004; Sey et al., 2008). Thus, there is limited consensus on the pattern of changes in SOM mineralisation and nutrient release across aggregates of different sizes. These diverging results may be related to the interactions of aggregates with different tillage practices [such as conventional (CT) and reduced tillage (RT) and no-till (NT)] and the return of different types of crop residues in soil systems (Carbonetto et al., 2014; Zhang et al., 2014; Tian et al., 2015, 2016; Bimüller et al., 2016).

Inputs of crop residues can potentially increase the mineralisation of native SOM by influencing microbial biomass and activity *via* co-metabolism (Blagodatskaya and Kuzyakov, 2008; Guenet et al., 2010), and also through 'nutrient mining' by microbes, particularly when C-rich residues are returned in nutrient-poor soil systems (Kuzyakov, 2002; Guenet et al., 2010). Further, the lability and nutrient content in different types of added crop residues can also affect the mineralisation of native SOM (Soon and Arshad, 2002; Chen et al., 2014). There are some studies that have enhanced our understanding on the effect of aggregate-size classes on the priming of SOC mineralisation following labile organic inputs (*e.g.* glucose) at different rates, showing a greater positive priming effect in macro-*versus* micro-aggregates (Tian et al., 2015, 2016). Some further studies have also made a simultaneous assessment of the dynamics of C and nitrogen (N) mineralisation in contrasting aggregate-size classes (Wu et al., 2012; Bimüller et al., 2016). As the processes such as degradation of crop residues and accelerated mineralisation of SOM may in turn release simple organic acids (Guppy et al., 2005; Kumari et al., 2008), these processes could further facilitate the release of nutrients such as phosphorus (P) and sulphur (S) from soil aggregates *via* dissolution and desorption reactions (Guppy et al., 2005; Keiluweit et al., 2015). These reactions may vary across soil types due to differences in clay content, clay mineralogy and polyvalent cations (such as Ca^{2+}, Mg^{2+}, Fe^{2+}, Al^{3+}) (Saidy et al., 2013; Fink et al., 2016). Further, these reactions may be more prominent in micro-aggregates with greater specific surface area and ion sorption-desorption capacity than in macro-aggregates (Six et al., 2002; Bimüller et al., 2016).

There have been no studies on the quantitative influence of different types of crop residues on the priming of native SOC mineralisation and the release of available N, P and S from the soil reserves in aggregate-size classes from different tillage systems. This understanding will be useful to underpin SOC modelling and nutrient management to support productivity and C sequestration in different farming systems (Kirkby et al., 2016; Luo et al., 2016). The aim of this study was, therefore, to increase our understanding of how, and to what extent, different aggregate-size classes, tillage intensity systems, and residue type interact to influence priming of SOC mineralisation and release of available nutrients in two contrasting soils.

In the current study, we propose two broader hypotheses, *i.e.*, the first one on the aspect of SOC mineralisation and the second one on the aspect of nutrient availability in contrasting soils:

(i) Regardless of tillage intensity, macro- and mega-*versus* micro-aggregates will have higher mineralisation of native SOC *via* positive priming following crop residue input, likely due to higher microbial activity and SOM bioavailability (Six et al., 2002; Zhang et al., 2014). Further, tillage (CT/RT) *versus* no-till (NT) will enhance residue C and native SOC mineralisation, which could be greater in coarser aggregates with low structural stability than finer aggregates (Six et al., 1998, 2002). Canola *versus* wheat residue, with high decomposability and intrinsic nutrients, will enhance mineralisation of native SOC in each aggregate class *via* positive priming, and that the priming effect will be greater in a clay-poor soil than clay-rich soil.

(ii) Consistent with SOC mineralisation, the net release of available nutrients will be higher in macro- and mega-*versus* micro-aggregates. Further, CT/RT *versus* NT systems and canola *versus* wheat residue will result in a greater release of plant available nutrients, possibly from SOM- and mineral-bound nutrient reserves in soil aggregates, which may vary with soil type (*e.g.* greater in a SOM- and clay-rich soil *versus* a SOM- and clay-poor soil).

To test these hypotheses, we incorporated ^{13}C labelled wheat and canola straw into three differently sized aggregates (mega-, macro- and micro-aggregates) to differentiate C mineralisation from residue and native SOM. The aggregate samples were obtained from two long-term tillage trials with contrasting soils, thus assessing the combined effect of aggregate-size classes, tillage intensity, crop residue type and soil type on the priming of aggregate-associated SOC and net nutrient (N, P and S) availability over 126 days. Similar to other recent studies (Bimüller et al., 2016; Tian et al., 2015, 2016), soil aggregate classes of different sizes were separated by a dry (rather than wet) sieving approach in the current study. This is because the dry sieving can: (i) retain dissolved OM within each aggregate class, (ii) cause minimal transfer of microbial communities across aggregates (*e.g.* from macro-to micro-aggregates), and (iii) cause minimal disruption of microbial habitat in the separated aggregates.

2. Materials and methods

2.1. Soils

Soils used for this incubation study were collected from two long-