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Soil with high organic carbon concentration continues to sequester carbon with increasing carbon inputs

S.E. Orgill [a,b,*], J.R. Condon [b], C.A. Kirkby [c], B.A. Orchard [a], M.K. Conyers [a,b], R.S.B Greene [d], B.W. Murphy [e]

[a] NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, NSW 2650, Australia
[b] Graham Centre for Agricultural Innovation, School of Agricultural & Wine Sciences, Charles Sturt University, Wagga Wagga, NSW 2650, Australia
[c] CSIRO, Agriculture, GPO Box 1600, Canberra 2601, Australia
[d] Australian National University, Acton, ACT 2601, Australia
[e] NSW Office of Environment and Heritage, Cowra, NSW 2794, Australia

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ABSTRACT

Identifying soil with a large potential to accumulate organic carbon (OC) could maximise the mitigation benefits of carbon (C) sequestration and help prioritise resources to achieve increases in soil OC. The purpose of this laboratory incubation experiment was to determine if an upper limit to OC accumulation in soil was approached with increasing C input in basalt- and granite-derived soil. For each parent material, two soil layers were compared to observe OC accumulation in soil with a high OC concentration (0 to 0.10 m, A1 horizon) and soil with a low OC concentration (0.40 to 0.50 m, B2 horizon). Soil samples were incubated for up to 146 days. The experiment consisted of three soil incubation cycles, with four treatments applied at the start of each cycle: soil only (control), soil and nutrients only (nutrients), high organic matter (OM) and nutrients (approximating a field equivalent of 12.4 Mg DM/ha; HOMN) and very high OM and nutrients (31.1 Mg DM/ha; VHOMN). At the beginning of cycle one ^{13}C labelled OM was applied. There was no asymptotic behaviour between C inputs and OC accumulation in soil observed in this study. Thus, OC accumulation was not approaching an upper limit for either parent material at OM application rates ranging from field equivalents of 12.4 to 93.3 Mg DM/ha (equivalent to 5.4 to 40.6 Mg C/ha). There was no significant increase in OC concentration between cycle 2 and 3 for the VHOMN treatment in the granite-derived 0.40 to 0.50 m soil. While this is not conclusive, this may indicate the soil is approaching an upper limit to OC accumulation at a lower OC concentration due to the dominance of 1:1 clays, compared to the 2:1 clay dominated basalt-derived soil. This suggests that mineralogy rather than texture may influence OC accumulation and any potential C saturation behaviour of soil. Despite increasing microbial activity, evidenced by increasing soil respiration ($P < 0.001$) and microbial biomass C ($P < 0.05$), as well as a significant ($P < 0.05$) narrowing of the C:N ratio of soil, there was substantial ^{13}C recovery (mean between 19.8 and 25.9 (1.1 se) % for both parent material) at the end of the soil incubation. This supports the hypothesis that the increases in OC accumulation were at least partly due to the conversion of plant residues into microbial detritus which is a major component of the relatively stable pool of OC in soil.

1. Introduction

The accumulation of organic carbon (OC) in soil is important for mitigating climate change, as well as sustaining environmental services and agricultural productivity (Lal, 2004). Identifying soil with the greatest carbon (C) sequestration potential can maximise these benefits, and help prioritise resources to achieve increases in soil OC. The ability of soil to accumulate OC is a balance between organic matter (OM) supply, primarily from *in situ* net primary productivity, and OM loss, principally through decomposition and erosion (Baldock et al., 2004). However, the relationship between OM inputs and increases in soil OC are not always linear, and an upper limit to OC accumulation has been proposed (Six et al., 2002; Stewart et al., 2007; Stewart et al., 2008b).

Land management practices that maximise plant productivity and minimise physical soil disturbance are likely to increase OM supply, and where this increase in OM is greater than the rate of OM decomposition, soil OC is therefore likely to increase (Lal, 2004; Luo et al., 2010; Paustian et al., 1997a; West and Post, 2002). While there have been several field trials where increased OM supply continued to increase soil OC (Huggins et al., 1998a; Kong et al., 2005; Paustian et al., 1997b), there have been numerous long-term trials where there was no increase in

* Corresponding author at: NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, NSW 2650, Australia.
E-mail addresses: Susan.Orgill@dpi.nsw.gov.au (S.E. Orgill), JCondon@csu.edu.au (J.R. Condon), Clive.Kirkby@csiro.au (C.A. Kirkby), Beverley.Orchard@dpi.nsw.gov.au (B.A. Orchard), Mark.Conyers@dpi.nsw.gov.au (M.K. Conyers), Richard.Greene@anu.edu.au (R.S.B. Greene), brian.amaroo@bigpond.com (B.W. Murphy).

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soil OC with continued OM input (Campbell et al., 1991; Gulde et al., 2008; Huggins et al., 1998a; Huggins et al., 1998b; Reicosky et al., 2002). To explain disparities such as these, the concept of soil C saturation was introduced (Six et al., 2002). It has been proposed that soil approaches an upper limit of OC accumulation, C saturation, based on inherent soil properties, including: soil texture, structure, mineralogy and chemistry (Six et al., 2002; Stewart et al., 2007; Stewart et al., 2008b). This concept challenges soil OC models that are based on linearity between soil C inputs and soil OC concentration (West and Six, 2007) and has practical implications for identifying and mapping soil with C sequestration potential (Angers et al., 2011; Chan et al., 2008).

Carbon saturation is defined as the point where with increased OM supply the whole soil, or a defined soil fraction, reaches a new higher steady state of OC (Six et al., 2002). This is based on soil properties and processes that are important for OC stabilisation. A large proportion of soil OC is associated with the fine fraction of soil; that is, silt- and clay-sized particles (Baldock and Skjemstad, 2000; Kahle et al., 2002a; Kahle et al., 2002b). Clay content, mineral surface area and reactivity can affect the amount of OM that is protected through adsorption within clay mineral assemblages (Greene et al., 1973), thereby restricting microbial access (Baldock and Skjemstad, 2000; Krull et al., 2003). As clay minerals have a finite surface area, the fine fraction is suggested to be more likely to reach C saturation than the whole soil where OC can readily accumulate in the form of particulate OM (Gulde et al., 2008; Hassink and Whitmore, 1997; Stewart et al., 2008b). Kleber et al. (2007) proposed that OC compounds sorb onto mineral surfaces in a self-organising and zonal sequence, often with varying thickness of OC and discontinuous coverage on mineral surfaces. While the protection of OM is greatest in the contact zone where organo-mineral associations form, this model enables clays to stabilise OC beyond their finite surface area. Biochemical alteration of OM during decomposition is another important stabilisation mechanism, where decomposed OM and the associated microbial products may be less vulnerable to further microbial attack and more likely to bond with clay minerals (Cadisch and Giller, 1997; Six et al., 2002). Lastly, the physical occlusion of OM in soil aggregates protects OM by limiting microbial access to OM, reducing oxygen diffusion and enhancing organo-mineral associations (Golchin et al., 1994a; Golchin et al., 1994b; Golchin et al., 1995; Grandy and Robertson, 2007; Oades, 1988; Tisdall and Oades, 1982).

Thus the capacity to increase soil OC concentration is largely determined by the clay content and clay mineralogy, as well as soil OC concentration and the quantity, continuity and chemical composition of OM input to soil. The C input required to achieve soil C saturation is commonly estimated by comparing the current soil OC concentration with the storage capacity of the fine fraction (silt- and clay-sized particles) or the whole soil, thereby calculating the C saturation deficit (Angers et al., 2011; Hassink and Whitmore, 1997), or by using asymptotic regressions between increases in soil OC concentration and C input (Stewart et al., 2008b). Based on these estimates, literature indicates that some soil OC fractions will exhibit C saturation behaviour, while others may not (Chung et al., 2008; Chung et al., 2010; Gulde et al., 2008; Kong et al., 2005; Stewart et al., 2008b). However, a recent study suggested these calculations may underestimate C storage in the fine fraction of soil due to i) limitations of the regression models and inadequate representation of soils at true C saturation, and ii) not accounting for differences in the specific surface area of clay minerals (Feng et al., 2013a).

Another reason why soil may not exhibit C saturation behaviour is due to biochemical stabilisation of OC in soil. Stewart et al. (2008a) suggested that biochemically stabilised OC may be independent of texture and mineralogy. Recent literature emphasises that rather than the traditional macromolecular model of humus (Stevenson, 1994; Tate, 1987), OM in soil is instead a 'continuum of progressively decomposing organic compounds' (Lehmann and Kleber, 2015). That is, OM in soil exists with varying degrees of stability and not in discrete pools. We use the term humus to refer to an experimental, rather than operational pool of soil OC, and acknowledge that OM in soil is a continuum and ranges from macro to micro-molecules. Assuming humus is biochemically a relatively stable form of soil OC (Magid and Kjærgaard, 2001; Soil Science Society of America, 2008; Tate, 1987), and represents the largest fraction of OC in most Australian agricultural soils (Beckwith and Butler, 1983; Kögel-Knabner, 2002; Stevenson, 1994), the potential of humus to accumulate in soil warrants more attention. In an incubation experiment using different rates of wheat straw and nutrients, Kirkby et al. (2013) demonstrated that where adequate OM and soil nutrients are available, humus can be formed irrespective of soil type and OC concentration. Their study, along with others (Cadisch and Giller, 1997; Dijkstra et al., 2006; Himes, 1997; Kindler et al., 2009) support the theory that humus is largely composed of microbial detritus. Consequently, the process of accumulating microbial mass and debris may negate soil approaching C saturation. If this is the case, so long as C and nutrient inputs to the soil are maintained, then even soil with a high OC concentration should continue to accumulate OC. The limit will then become the environmental and economic feasibility of sustaining these inputs, and not just the inherent soil properties.

While studies have estimated and measured C saturation of the whole soil and soil fractions, few have assessed: i) soil under agricultural management with a high OC concentration and ii) the potential of soils with a low OC concentration, such as subsoils, to sequester C. Fewer studies have applied nutrients at the rates based on the stoichiometry of humus to promote the biochemical stabilisation of OC in soil. This study used an incubation experiment to evaluate the relationship between OM and nutrient inputs, microbial activity and OC concentration in two contrasting soil types, and assessed whether or not soil with high OC concentration approached an upper limit to OC accumulation. A regional survey was used to identify three basalt- and three granite-derived soils with high OC concentration. The two parent materials (thus, soil types) were selected to compare OC accumulation in soil with contrasting mineralogy and particle size distribution. For each parent material, two soil depths were compared to observe OC accumulation in soil with a high OC concentration (0 to 0.10 m, A1 horizon) to soil with a low OC concentration (0.40 to 0.50 m, B2 horizon). Treatments were based on 2 and 5 year pasture growth estimates for these parent materials, and nutrient rates were based on the stoichiometry of humus and achieving 30% stabilisation of OM added to soil. We hypothesised that for a given soil type, soil with a high OC concentration will continue to accumulate OC in a relatively stable form if both C and nutrient inputs are maintained.

2. Methods

2.1. Experimental design

Six permanent pasture sites, three with basalt-derived soil and three with granite-derived soil, were identified as having the highest OC concentration for their parent material class from a field survey in the Monaro region, south eastern Australia (Orgill et al., 2014). Two soil layers (0 to 0.10 and 0.40 to 0.50 m) were sampled from these sites for this experiment in September 2013. The treatment and measurement schedule for this experiment is provided in Fig. 1. The experiment consisted of three soil incubation cycles where samples were incubated in a darkened constant temperature room (CTR) at 25 °C. The six sites were divided into two groups; Group A and Group B. Group A included one basalt and one granite site, four treatments (discussed below) and measurements included: soil respiration, soil OC and N concentration and microbial biomass carbon (MBC). Group B samples (two basalt and two granite sites) had only two treatments and soil OC and N concentration measured (Fig. 1). The purpose of Group B was to ensure that the inference for soil OC from this study could be generalised to other basalt- and granite-derived soils in the Monaro region. The experiment was designed as a four replicate split-plot design with cycle randomised