Geoderma 313 (2018) 52–56

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Funding body: Department of Agriculture Food and Marine.

Effects of soil type and depth on carbon distribution within soil macroaggregates from temperate grassland systems

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ARTICLE INFO

Handling Editor: I. Kögel-Knabner

Keywords:
Soil organic carbon
Soil aggregation
Subsoil
Grassland

ABSTRACT

Grassland soils have been highlighted as a global soil carbon (C) sink, and have the potential to sequester additional C. Sequestration of C can occur through incorporation of soil organic carbon (SOC) within microaggregates and the silt and clay fractions. The distribution of SOC within macroaggregate fractions gives an insight into both SOC dynamics and its incorporation into the soil. Research to date on soil C has tended to focus on the topsoil (0–30 cm). While many studies have assessed the changes in aggregation and SOC dynamics after land use or management change, this paper assesses aggregation and SOC dynamics in the topsoil and subsoil of twenty-one temperate grassland sites covering four soil types (Haplic Luvisol, Haplic Stagnosol, Haplic Cambisol, Stagnic Cambisol). Results show that there are no differences in SOC between soil types in the surface 0–30 cm, except a decrease in the quantity of microaggregates within macroaggregates in Haplic Stagnosols. In the subsoil, the silt and clay fraction of clay-illuviated soils had a lower percentage of SOC. Soils with clay illuviation and reducing conditions had a decreased proportion of SOC in microaggregates and silt plus clay within small macroaggregates in the subsoil. This could be caused by a combination of (i) reduced incorporation of SOC into smaller fractions, because POM inputs could be limited due to soil saturation limiting root growth, and (ii) reduced mineralisation and subsequent incorporation of POM into microaggregates and silt plus clay within macroaggregates. These results enable elucidation of the mechanisms driving aggregate formation (and thus C sequestration in microaggregates and silt plus clay fractions) in topsoil and subsoil. This study shows that the dynamics of SOC in subsoil horizons is soil-type dependant and that differences between soil types cannot be elucidated when the sampling is limited to 30 cm. This suggests that the IPCC guidelines for SOC measurements should also include the sampling of subsoil horizons in order to get valuable information that allows discerning between soil types.

1. Introduction

Soil aggregation has several benefits for agriculture and the environment: It enhances aeration, structure, water holding capacity and infiltration, which improves root establishment and plant growth (Bot and Benites, 2005; Lal, 2004; Stevenson, 1994). Aggregation physically partitions soil organic matter (SOM) from microorganisms and their enzymes, thus limiting mineralisation of SOM and CO_2 emissions to the atmosphere (Cambardella and Elliott, 1992; Six et al., 2002a, 2002b). Therefore, it plays an important role in carbon (C) sequestration.

Aggregates are formed through the association of SOM with the mineral fraction of the soil. When bacteria decompose particulate organic matter (POM), mucilaginous glycoproteins are secreted. At the same time, fungal hyphae and roots physically hold together the POM and the mineral fraction of the soil. Both factors mediate POM encrustation by the mineral fraction, creating a macroaggregate (> 250 μm) (Oades, 1984; Tisdall and Oades, 1982). When POM gets further decomposed, it decreases in size (Guggenberger et al., 1994) and it becomes encapsulated by mineral compounds in smaller structures: microaggregates (53–250 μm) and silt plus clay sized aggregates and particles (< 53 μm), which serve as building blocks for the formation of new macroaggregates when the POM is too small to keep the microaggregates together (Six et al., 1998). Oxygen diffusion is often reduced at the centre of microaggregates and further at the centre of silt

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http://dx.doi.org/10.1016/j.geoderma.2017.10.012
Received 3 May 2017; Received in revised form 22 August 2017; Accepted 10 October 2017

plus clay sized aggregates (Sexstone et al., 1985). Consequently, the SOM contained inside these microaggregates is not easily accessed by microorganisms and the mean residence time of SOM associated with microaggregates and the silt plus clay fraction is higher than that in macroaggregates (Six et al., 2002a, 2002b). Therefore, the incorporation of SOC into microaggregates and the silt plus clay fraction is a mechanism for C sequestration (Skjemstad et al., 1990). Carbon associated with microaggregates within macroaggregates has been highlighted as an early indicator of SOC changes associated with management practices (Six and Paustian, 2014).

While some studies have assessed SOC distribution within the different aggregates sizes in grassland soils (Bach et al., 2010; Wang et al., 2015), most of the research regarding the formation of microaggregates within macroaggregates focuses on the effects of management practices, such as tillage (Denef et al., 2004; Mikha and Rice, 2004; Zibilske and Bradford, 2007). It has been shown that management influences macroaggregate turnover whereby slower macroaggregate turnover enhances the formation of microaggregates within macroaggregates, which increases C sequestration (Six et al., 2000). In contrast, if the soil is disturbed macroaggregates are broken, releasing microaggregates and POM, which becomes a source of SOC for bacteria and causes a depletion of SOC (Six et al., 2000). Despite the importance of grassland in temperate regions, studies on the effect of soil type on the formation of microaggregates are limited (O'Brien and Jastrow, 2013; Torres-Sallan et al., 2017).

Several studies highlight the importance of assessing the dynamics of SOM in subsoil: Salomé et al. (2010) revealed that the regulation of SOC cycling is different in subsoil compared to topsoil. Other studies indicate that the chemical composition of SOM in subsoil is affected by pedological processes and is therefore soil-type specific (Eusterhues et al., 2005; Rumpel et al., 2002). Some management practices such as drainage or ploughing have an impact in subsoil (Baker et al., 2007; Tan et al., 2002; Veenstra and Lee Burras, 2015). While the dynamics and mechanisms affecting subsoil SOC are subject to increasing scientific scrutiny, to date, most of the research concerning SOC dynamics and aggregation has focused on the topsoil. To our knowledge, all studies assessing the fractions within macroaggregates focus on the top 20 cm of soil (see review of Six and Paustian, 2014). Rumpel and Kögel-Knabner (2011) suggested that there are knowledge gaps regarding the mechanisms affecting aggregation and SOC stabilization in subsoils.

The aim of this paper is to understand the effect of soil type and depth on aggregate formation and to assess the factors affecting the incorporation of SOC within macroaggregates in horizons to 1 m depth. This will improve understanding of differences in SOC dynamics between soil types, and inform the discussion on how management practices can be adapted to increase SOC storage in soils. The hypothesis is that different soil types have different distributions of SOC within macroaggregate fractions, as a result of differences in characteristics that influence aggregate formation.

2. Materials and methods

2.1. Soil selection and sampling

Twenty-one permanent grassland sites, mainly managed as improved grasslands, over a wide variety of bedrock types (i.e. sandstone, shale, gneiss, schists and limestones) and drift (igneous and metamorphic, siliceous and limestone) were selected with the aim of being a representative set of the main four soil types occurring in Irish Grasslands. These are six Haplic Stagnosols (Typical Surface-water Gleys in the Irish classification), three Haplic Luvisols (Typical Luvisols in the Irish classification), five Stagnic Cambisols (Stagnic Brown Earths in the Irish classification, and seven Haplic Cambisols (Typical Brown Earths in the Irish classification). Table 1 shows the SOC stock and texture of the each soil type. For each site, a pit was dug to 1 m depth where possible, and each horizon was described following the FAO field handbook *Guidelines for soil description* (FAO, 2006) and sampled. Soils were classified according to the Irish Soil Information System (Simo et al., 2014). For each horizon, 1 kg of sample was taken and stored at 4 °C until use.

2.2. Aggregate separation

A 300 g subsample was gently passed through an 8 mm sieve, and dried at 40 °C for one week. Following an adaptation of the method described by Cambardella and Elliott (1993), small macroaggregates (250–2000 μm) were isolated, dried, and stored at room temperature until use.

The isolation of POM, microaggregates and silt plus clay within macroaggregates was done following the methodology proposed by Six et al. (2000). Briefly, 10 g of small macroaggregates were placed on the top of a 250 μm mesh with 50 glass beads (4 mm diameter), and gently shaken under a continuous water flow that washed the smaller material into a 53 μm sieve without breaking up the microaggregates within macroaggregates. The POM and sand were recovered from the 250 μm mesh once there were no macroaggregates remaining. To ensure that only water-stable microaggregates within macroaggregates were isolated, the material remaining on the 53 μm sieve was wet sieved at a constant rate. During this process, microaggregates within macroaggregates were separated from the silt plus clay within macroaggregates fraction. All fractions were dried, weighed, ball milled and stored for SOC analysis.

The proportion of microaggregates within macroaggregates was calculated according to Six et al. (2000), with the following Eq. (1):

$$\frac{\text{microaggregate weight} - \text{weight of 53 to 250}\mu\text{m sized sand}}{\text{macroaggregate weight} - \text{weight of 250 to 2000 }\mu\text{m sized sand}} \quad (1)$$

2.3. Soil organic carbon analysis

Carbonates within each sample were removed with an acid fumigation method (Harris et al., 2001). Briefly, a ball-milled subsample was weighted and placed in a vacuum chamber, where a HCl atmosphere was created by adding two beakers with concentrated HCl and creating a vacuum. The SOC associated with each fraction was analysed with a LECO Truspec CN analyser following ISO 10694:1195.

The proportion of SOC in each fraction within macroaggregate was calculated with Eq. (2):

$$\frac{mg\ SOC\ in\ fraction}{g\ fraction\ (including\ same\ sized\ sand)} \times \frac{g\ fraction\ (including\ same\ sized\ sand)}{g\ macroaggregate} \quad (2)$$

2.4. Statistical analysis

Physical and chemical data (SOC, CEC, pH, texture, bulk density) was obtained from the database of the Irish Soil Information System (Creamer et al., 2014). The effect of depth and soil type on the percentage of aggregation and the SOC distribution within aggregate fractions was analysed using PROC MIXED in SAS (version 9.3). After checking the residuals, log transformations were needed to ensure that the data fitted the assumptions required for the analysis. The Duncan test was used to check the differences between soil types.

3. Results

3.1. Carbon concentration and proportion associated with the different fractions within macroaggregates

In the topsoil, there was no difference in SOC content between soil