Agriculture, Ecosystems and Environment 200 (2015) 79–87

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Contribution of roots and amendments to soil carbon accumulation within the soil profile in a long-term field experiment in Sweden

Lorenzo Menichetti [a,*], Alf Ekblad [b], Thomas Kätterer [c]

[a] Swedish University of Agricultural Sciences, Department of Soil and Environment, P.O. Box 7014, Uppsala 75007, Sweden
[b] School of Science and Technology, Örebro University, Örebro 70182, Sweden
[c] Swedish University of Agricultural Sciences, Department of Ecology, P.O. Box 7044, Uppsala 75007, Sweden

ARTICLE INFO

Article history:
Received 5 December 2013
Received in revised form 30 October 2014
Accepted 3 November 2014
Available online xxx

Keywords:
$\delta^{13}C$
Root humification
SOC
Subsoil
Topsoil

ABSTRACT

The contribution of different C inputs to organic carbon accumulation within the soil profile in the Ultuna long-term continuous soil organic matter experiment, established in 1956, was determined. Until 1999, C_3-crops were grown at the site, but since then maize (C_4) has been the only crop. The effect of a total of 10 different inorganic nitrogen and organic amendment treatments (4 Mg C ha^{-1} yr^{-1}) on SOC in topsoil and subsoil after 53 years was evaluated and the contribution from maize roots to SOC after 10 years of cultivation was estimated.

Soil organic carbon (SOC) and $\delta^{13}C$ signature were measured down to 50 cm depth. The C content in the topsoil (0–20 cm depth) was 1.5% at the start of the experiment. After 53 years of treatments, the average topsoil C content varied between 0.9 and 3.8% of soil dry weight, with the open fallow having the lowest and the peat amended the highest value. Nitrogen seemed to promote C accumulation in the topsoil treatment effects were smaller below 20 cm depth and only two of the amendments (peat and sewage sludge) significantly affected SOC content down to 35 cm depth. Despite this, penetrometer measurements showed significant treatment differences of compaction below 41 cm depth, and although we could not explain these differences this presented some evidence of an initial treatment-induced subsoil differentiation. Ten years of maize growth affected the $\delta^{13}C$ of SOC down to 22.5 cm depth, where it varied between −25.16 and −26.33(‰), and an isotopic mass balance calculation suggested that maize C accounted for 4–8% of total SOC in the topsoil. Until less than 2500 years ago the site was a post-glacial sea floor and the ^{14}C data suggest that marine sediment C still dominates the SOC in deeper soil layers. Overall, the results suggest that 53 years of treatments has caused dramatic changes on the stored C in the topsoil in several of the treatments, while the changes in the subsoil is much less dramatic and a small C accumulation in the upper subsoil was found in two of the treatments.

The contribution from roots to SOC accumulation was generally equal to or greater than the contribution from amendments. The retention coefficient of root-derived C in the topsoil was on average 0.30 ± 0.09, which is higher than usually reported in the literature for plant residues but confirms previous findings for the same experiment using another approach. This strengthens the conclusion that root-derived SOC contributed more to SOC than above-ground crop residues.

1. Introduction

The global carbon (C) sink is expected to increase with the increase in primary productivity driven by higher temperatures and CO_2 concentrations (Kirschbaum, 2000). However, a simultaneous increase in emissions due to land use change or an increase in soil respiration after an increase in temperature may counteract almost all this positive effect (Eglin et al., 2010). More than one-third (37%) of global land is used in agriculture and 10% of global land is under annual crops (FAO Statistical Database, 2013), and therefore exposed to quick changes in management. On agricultural land, the range of possible interventions for climate change mitigation is constrained by the global requirements for food production (Powell and Lenton, 2012), but C sequestration in agricultural soils can be increased through changes in management practices (Lal, 2004; Kätterer et al., 2013; Stockmann et al., 2013).

Most previous studies on C sequestration have focused on the topsoil (e.g., Lorenz and Lal, 2005). Although this is understandable, since the concentrations and turnover of SOC are usually

* Corresponding author. Tel.: +46 7 68549268; fax: +46 18673156.
E-mail address: Lorenzo.Menichetti@slu.se (L. Menichetti).

http://dx.doi.org/10.1016/j.agee.2014.11.003
0167-8809/

higher in topsoils than in subsoils, globally subsoils store more than half of total SOC (Jobbagy and Jackson, 2000) and are therefore potentially important for C sequestration strategies. A few studies have been conducted (e.g., Paul et al., 1997; Jobbagy and Jackson, 2000; Bird and Kracht, 2003; Jenkinson and Coleman, 2008; Jenkinson et al., 2008; Kirchmann et al., 2013), but there is still relatively large uncertainty regarding C in deeper soil layers (Lorenz and Lal, 2005). Areas of uncertainty include the response to changes in management of a large part of the C stored in soil (Poeplau et al., 2011) and its stabilization mechanisms (Chabbi et al., 2009), making precise quantitative predictions difficult. It is therefore important to obtain accurate information on the reactivity of different C pools to management changes and on how different C inputs contribute to the formation of SOC over the whole soil profile. In particular, the contribution of root-derived material can be particularly relevant for SOC accumulation because of the possible associated protection mechanisms (Rasse et al., 2005), and might so far be underestimated in the literature (Kätterer et al., 2011).

During recent decades, long-term experiments have been shown to produce information on the formation of SOC stocks from different organic C inputs (Kätterer et al., 2011) and on how the older SOC decays (Barré et al., 2010). Therefore in this study we used data from the Ultuna long-term field experiment, established in Sweden in 1956 and managed since then by additions of a fixed amount of C in the form of different amendments, in combination with or without nitrogen (N) fertilization.

The aim of the study was to examine the following questions: (1) How have N fertilization and addition of organic amendments affected SOC accumulation in topsoil and subsoil in the Ultuna long-term field experiment? and (2) How have C inputs from roots contributed to SOC formation and accumulation?

To determine how management practices affect soil C accumulation or release in agricultural topsoil and subsoil, we analyzed soil cores from 0 to 50 cm depth in 10 different experimental treatments. This allowed us to evaluate the effect of different C inputs on SOC stocks on the whole soil profile since the start of the experiment in 1956.

To consider the inputs from roots, we based our investigation on the fact that the crops cultivated in the experiment shifted from C_3 to C_4 crops in the year 2000. Several authors have tried to determine the decay of SOC of different ages by exploiting the natural difference in ^{13}C content of plants with C_3 and C_4 photosynthetic cycles (Wynn and Bird, 2007; Blagodatskaya et al., 2011). The analysis of $\delta^{13}C$ signatures down the whole soil profile allowed us to quantify the contribution to SOC from maize rhizodeposition to a depth of 50 cm over 10 years in the different experimental treatments. We then determined the retention coefficient of the newly formed material for each experimental treatment, investigating the influence of rhizodeposition on SOC accumulation and decay at different depths.

2. Material and methods

2.1. Study site and treatments

The long-term field experiment is located in Ultuna, close to Uppsala (59.82 °N, 17.65 °E), in a Dfb climate (warm summer hemiboreal) according to the Köppen classification (Peel et al., 2007), with mean annual precipitation of 570 mm and mean annual air temperature of +5.4 °C. The topsoil (0–20 cm) is a clay loam with 36.5% clay, 41% silt (0.002–0.06 mm) and 22.5% sand (0.06–2 mm) and is classified as a Eutric Cambisol (IUSS Working Group, 2007). The parent material consists of post-glacial sediments and illite is the main clay mineral (Gerzabek et al., 1997). In 1956, the topsoil had an organic C content of 1.5%, an N content of 0.17% and a pH of 6.6. The site has been in agricultural use for at least 300 years. Since the start of the experiment, the plots have been cultivated manually.

From 1956 to 1999, annual C_3 crops such as oats, spring barley, sugar beet, oilseed rape, turnip rape and white mustard were cultivated. Prior to 2000, cultivated plants had an average $\delta^{13}C$ signature of -28.0 ± 0.1‰ (Menichetti et al., 2013). In 2000, C_3 crops were replaced with forage maize, a plant with a C_4 photosynthetic cycle and an average $\delta^{13}C$ signature of -12.3 ± 0.1 ‰ (Menichetti et al., 2013).

The experimental design consisted of 15 treatments with four replicate plots in a randomized block design. Each plot is 2 m × 2 m, separated by 40 cm high steel frames extending to a depth of 30 cm. Approximately the same amount of C (~4 Mg ha^{-1}) is added in 10 of the treatments in autumn every second year as different organic amendments (Table 1). Inorganic N fertilizer is added annually during spring at a rate of 80 kg N ha^{-1} yr^{-1} in the N-fertilized treatments. The experiment also includes a treatment that receives neither N fertilizer nor organic amendments and a bare fallow treatment that is kept free from vegetation by regular weeding. All plots are fertilized annually with 22 kg P and 35–38 kg K ha^{-1}. Above-ground biomass is harvested by cutting the crop close to the soil surface, and both grain and above-ground yields are recorded each year. A sample archive, managed together with the experiment, stores samples from topsoil, plant materials and amendments taken every second year since 1983 and intermittently between 1956 and 1982. From the 15 treatments, the subset of 10 selected for this study covered the whole range of SOC quality in the experiment (Table 1).

2.2. Sampling and analysis

Soil sampling was carried out after crop harvest in September 2009. Samples were taken with an auger at increasing depth intervals of: 0–15, 15–17.5, 17.5–20, 20–22.5, 22.5–25, 25–27.5, 27.5–30, 30–35, 35–40 and 40–50 cm. These sampling depths have been chosen to increase the resolution in the intervals with more

Table 1
Topsoil (0–20 cm) characteristics (means with standard errors; $n = 4$) of treatments A–O in the Ultuna long-term experiment studied here.

Treatment	Crop	Fertiliser[a] (80 kg N ha^{-1} yr^{-1})	Amendment (4 Mg C ha^{-1})	δ^{13}C 1999 (‰)	δ^{13}C 2009 (‰)	C 2009(%)	N 2009(%)	C/N 2009	δ^{15}N 2009 (‰)	Maize yields (Mg ha^{-1})	Bulk density 2009
A	No	No	No	−26.1 ± 0.0	−25.2 ± 0.4	0.97 ± 0.02	0.11 ± 0.00	8.2	8.1 ± 0.3	NA	1.43 ± 0.06
B	Yes	No	No	−26.7 ± 0.1	−25.6 ± 0.1	1.12 ± 0.02	0.12 ± 0.01	8.3	8.0 ± 0.2	3.3 ± 0.2	1.40 ± 0.02
C	Yes	Yes	No	−26.5 ± 0.0	−25.5 ± 0.1	1.37 ± 0.03	0.13 ± 0.01	10.0	7.6 ± 0.3	7.1 ± 0.4	1.28 ± 0.04
F	Yes	No	Straw	−26.9 ± 0.2	−25.9 ± 0.1	1.49 ± 0.01	0.15 ± 0.00	10.0	7.7 ± 0.1	4.1 ± 0.2	1.38 ± 0.07
G	Yes	Yes	Straw	−27.0 ± 0.1	−26.3 ± 0.2	1.92 ± 0.04	0.17 ± 0.02	10.6	6.8 ± 0.6	8.3 ± 0.5	1.21 ± 0.01
H	Yes	No	Green manure	−26.9 ± 0.1	−25.8 ± 0.2	1.54 ± 0.02	0.18 ± 0.00	8.9	7.4 ± 0.2	6.3 ± 0.2	1.34 ± 0.02
J	Yes	No	Farmyard manure	−27.1 ± 0.2	−26.3 ± 0.2	2.21 ± 0.05	0.20 ± 0.01	9.5	8.3 ± 0.4	8.2 ± 0.6	1.24 ± 0.05
M	Yes	Yes	Peat	−26.3 ± 0.1	−25.8 ± 0.1	3.78 ± 0.07	0.23 ± 0.01	15.7	5.0 ± 0.3	10.1 ± 0.6	1.05 ± 0.04
N	Yes	Yes	Sawdust	−26.1 ± 0.1	−25.4 ± 0.0	2.2 ± 0.05	0.16 ± 0.01	11.9	5.5 ± 1.2	7.7 ± 0.2	1.23 ± 0.08
O	Yes	No	Sewage sludge	−26.1 ± 0.0	−25.4 ± 0.1	2.66 ± 0.02	0.25 ± 0.02	9.6	7.6 ± 0.1	9.7 ± 0.1	1.02 ± 0.06

[a] Fertilised with $Ca(NO_3)_2$.