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Changes in organic carbon in topsoil and subsoil and microbial community composition caused by repeated additions of organic amendments and N fertilisation in a long-term field experiment in Sweden

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ABSTRACT

The effects of 13 years of biennial application of four organic amendments (compost, green manure, farmyard manure and sewage sludge) on soil organic carbon (SOC) stocks, microbial biomass and community structure were compared with those of bare fallow, an unfertilised control and N-fertilised treatments. The experiment was conducted on a clay soil in western Sweden, in a randomised block design with four replicates. The crops grown were spring barley and oats. Changes in SOC mass were estimated by the 'equivalent soil mass' concept. Carbon inputs from crops were calculated from grain yields using linear allometric functions. The decomposition rate of soil organic matter was derived from a bare fallow treatment. Humification coefficients, defined here as the fraction of C input entering the SOC pool, for the organic amendments and crop residues were estimated by fitting a single-pool first order model to the final SOC stocks. The humification coefficient was highest for domestic waste compost (0.9) and lowest for above-ground crop residues (0.19). Crop yields were highest in sewage sludge-amended soil, probably due to favourable physical soil conditions, as indicated by lower bulk density (1.27–1.30 g cm^{-3}) than in the other treatments (1.32–1.38 g cm^{-3}). Despite addition of relatively high amounts of organic N, yields in other treatments receiving organic amendments were significantly lower than in those receiving mineral N fertiliser. In particular, the compost material was found to be highly recalcitrant, as indicated by its low C/N ratio (10) and low crop yield. Comparison of the correlation between phospholipid fatty acid (PLFA) concentration and SOC showed that compost supported relatively less microbial biomass than the other substrates tested. An important finding was that differences in SOC between treatments were significant to 40 cm depth and that up to 27% of the SOC changes observed to 40 cm depth occurred in the upper subsoil (25–40 cm). Thus, SOC changes below ploughing depth should be considered in SOC balance studies.

1. Introduction

Soil organic matter is essential for soil productivity and ecosystem functions (Johnston et al., 2009; Power, 2010). An understanding of changes in soil organic carbon (SOC) resulting from altered agricultural practices and land use is also important when designing mitigation strategies (IPCC, 2007; Lal and Follett, 2009). Long-term agricultural field experiments integrating management options over decades allow stringent evaluations of changes in SOC and can be used for calibration and validation of models predicting future changes (e.g. Rasmussen et al., 1998; Kätterer and Andrén, 1999), as pointed out by Jenkinson (1991) and Johnston (1997).

Plant residues, including roots and rhizosphere deposits, are quantitatively the largest source of SOC, and management options increasing crop production thus lead to an increase in carbon (C) inputs to soil (Kätterer et al., 2011; Lou et al., 2011; Kirchmann et al., 2013). In addition, organic wastes from society and livestock excreta are significant C sources for soil organic matter (Kätterer et al., 2012). The proportion of C from plant residues and organic wastes remaining in soil over a time scale of decades depends on substrate properties (e.g. Gerzabek et al., 1997; Peltre et al., 2012), although the molecular structure of a substrate alone does not

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determine its persistence in soil (Schmidt et al., 2011). Long-term field trials are indispensable for quantifying the effect of amendments and other management practices on SOC.

Although it is well known that large applications of C are positive for the C content in the tilled layer (topsoil), the effects on C stocks in subsoil are still scarcely investigated and the results reported in the literature are not consistent (Lützow et al., 2006; Fontaine et al., 2007; Jenkinson et al., 2008; Schlüter et al., 2011; Kirchmann et al., 2013). Input of C to the subsoil can occur through transport of dissolved organic C from the topsoil and through better crop growth, leading to formation of more roots. On the other hand, priming, i.e. increased decomposition of stabilised material induced by the addition of fresh organic material triggering microbial activity (Löhnis, 1926; Kuzyakov et al., 2000), can result in higher C losses from subsoils.

The objective of this study was to quantify the impact of mineral N fertilisers and organic amendments on SOC in the soil profile and to analyse the microbial biomass and community structure in a 13-year-old field experiment. The hypotheses tested in the study were that: (i) higher yields due to N fertilisation and addition of nutrient-rich amendments increase above-ground and below-ground biomass production and thereby increase SOC stocks in both topsoil and subsoil; (ii) an increase in SOC stocks in the subsoil is mainly caused by transport of organic matter from organic amendments added to the topsoil; (iii) the proportion of C retained in soil increases with degree of decomposition of the organic material before addition to soil, i.e. retention is lowest for above-ground plant biomass, intermediate from rhizodeposits, farmyard manure and sewage sludge and highest for domestic compost; and (iv) microbial community composition is affected more by soil physical and chemical conditions than by properties of the organic materials added to soil.

2. Materials and methods

2.1. Site description and experimental layout

The experiment was established in 1996 at Lanna agricultural research station (58.34°N, 13.10°E) in Western Sweden. The soil at the site is an Aquic Haplocryept developed on a Quaternary silty clay deposit (M. Simonsson, personal communication 2013). Mean annual temperature at the site was 7.3 °C and precipitation was 636 mm during the experimental period (1996–2009) according to data recorded at Lanna and at two other meteorological stations at a mean distance of 9.7 km away. The crops grown over the 13-year period 1997–2009 were oats (6 years) and spring barley (7 years).

The experiment was established with the nine treatments (A–I) described in Table 1, randomised within four blocks. Oats were grown in 1996 and grain yield was recorded for each plot separately to identify spatial gradients within the field. The rate of nitrogen (N) fertiliser applied to the oats was relatively low (40 kg N ha^{-1}) due to expected N delivery from crop residues after peas grown in 1995. Mean grain yield was 5.3 Mg dry matter ha^{-1} and a low standard deviation (0.3 Mg) indicated that the variability between plots was low. Yield did not differ between blocks, according to analysis of variance ($p = 0.25$).

All plots were mouldboard-ploughed in autumn after harvest. The bare fallow treatment was harrowed 4–5 times during the growing season and occasionally (not every year) treated with herbicides to control weeds. Plot area was 112 m^2 (30 plots) or 92 m^2 (4 plots). Treatments B and C received 20 kg P and 15 kg K ha^{-1} in spring 1996 and 1997, while from 1998 onwards 40 kg P and 30 kg K ha^{-1} were applied biennially in autumn. In treatments B and C, N fertiliser (80 kg N ha^{-1}) was applied annually in spring.

Table 1
Treatments in the Lanna field experiment, average dry matter grain yield 1999–2009 (7 years spring barley and 6 years oats), soil pH(H_2O) measured in 2010, soil dry bulk density (BD), soil organic carbon (SOC) concentration in different soil layers measured in September 2009 and SOC stocks equivalent to the mineral mass to either 25 or 40 cm depth (z_{eq}) in 1996 calculated from bulk density and C concentration. Organics amendments in treatments D–H were applied every second year at a rate of 8 Mg ha^{-1} ash-free dry mass (see also Table 2).

ID	Treatment/application	Yield[a] (Mg ha^{-1})	pH	BD[b] (g cm^{-3})	SOC (mg g^{-1})				z_{eq}		SOC (Mg ha^{-1})	
				0–22 cm	0–20 cm	20–25 cm	25–30 cm	30–40 cm	25 cm	40 cm	0–z_{eq25}	0–z_{eq40}
A	Bare fallow	–	6.4b	1.38a	18.3f	15.5e	12.3bc	5.2c	24.2	39.2	59.7	76.7
B	Calcium nitrate[c]	2.8a	6.6ab	1.36ab	19.2ef	18.2 cd	12.2bc	4.8c	24.5	39.5	63.8	79.9
C	Ammonium sulphate[c]	2.8a	6.1c	1.33bc	20.0de	18.7bcd	15.0ab	6.2abc	25.0	40.0	66.2	85.4
D	Grass hay[d]	1.3 cd	6.4b	1.33bc	20.9 cd	19.8bc	15.0ab	6.2abc	25.0	40.0	69.5	88.7
E	Farmyard manure[e]	1.6b	6.5b	1.32c	22.9b	20.6b	15.7a	6.8abc	25.2	40.2	75.4	95.6
F	Sludge[f]	3.0a	6.1c	1.30 cd	22.3bc	20.2bc	13.5abc	5.5bc	25.5	40.5	73.1	89.5
G	Sludge[f] + metals[g]	2.9a	6.1c	1.27d	23.4ab	20.0bc	15.7a	7.6ab	26.0	41.0	75.5	95.5
H	Compost[h]	1.4bc	6.7a	1.33bc	24.6a	24.1a	15.6a	8.1a	25.1	40.1	82.5	104.6
I	Unfertilised control	1.0d	6.4b	1.38a	18.7ef	17.1de	11.9c	4.7c	24.2	39.2	61.6	77.9

Different letters indicate significant treatment effects according to analysis of variance (*F*-test, $p < 0.05$) and significant differences between treatments according to LSD-tests.

[a] Grain dry mass.

[b] The value in treatment A refers to 12–22 cm depth, since the upper layer had been harrowed a few days before sampling.

[c] 80 kg N ha^{-1} yr^{-1}, but in 1996 only 40 kg N fertiliser were applied due to residual N after peas grown in 1995.

[d] The hay was mainly timothy.

[e] Farmyard manure came from a cowshed with straw bedding.

[f] Sludge was dewatered municipal anaerobically digested sewage sludge.

[g] Salts of Cd, Cu, Ni and Zn (0.098, 3.04, 6.25 and 0.179 kg ha^{-1}, respectively) are applied together with sewage sludge.

[h] Derived from domestic waste.