Direct and indirect effects of repeated addition of sewage sludge on soil carbon stocks evaluated in four Swedish long-term field experiments

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Abstract
The effect of repeated addition of sewage sludge on changes in soil carbon (SOC) stocks was evaluated in four long-term field experiments, between 13 and 53 years old. Soil samples were taken in 2009 and 2011 in the topsoil at all sites and to 40 or 70 cm depth two of the sites. Annual amounts of carbon added with sludge ranged from 0.32 to 2.1 Mg C ha^{-1} yr^{-1}. Sewage sludge addition to soil increased SOC directly through C input and indirectly through stimulation of primary production. Almost 50% of the changes in SOC occurred below the upper 20 cm layer or about a third below ploughing depth. Thus, SOC changes below the topsoil should be considered in soil C balance studies. Indirect positive feedbacks of sludge addition on soil fertility and the positive effect of N fertilization on SOC should also be considered.

Introduction

Soil organic matter is essential for soil fertility and other ecosystem services. Organic wastes from bioenergy extraction, food industry and waste-water plants recycled to agricultural land comprise a source for building soil organic carbon (SOC) and may result in SOC sequestration. When comparing different options for recycling of sewage sludge, e.g., in live cycle assessments, both direct and indirect effects have to be considered. The direct effect refers to input of C to soil with sewage sludge and the indirect effect to enhanced primary production and increased crop residue input. The objective of this study was to investigate the effects of sewage sludge application on SOC in four long-term field experiments. In long-term agricultural field experiments, management options affecting SOC are accumulated over decades and therefore constitute a useful platform and valuable database, for example, to calibrate or validate models used for predicting future changes [1]. In other words, to look forward we have to look back.

Material and Methods

Changes in SOC stocks were evaluated in four long-term field experiments run between 13 and 53 years (Table 1). Soil samples were taken in 2009 or 2011 in the topsoil (to 20 or 22.5 cm depth) at two sites and to 40 or 70 cm depth at the other two sites. Results from one of the sites were recently published [2]. Sewage sludge was incorporated every second or fourth year. Annual amounts of carbon added with sludge ranged from 0.33 to 2.11 Mg C ha^{-1} yr^{-1} (Table 2). Treatment effects were evaluated using analysis of variance and LSD-tests were applied to compare SOC between treatments.

Table 1. Properties of investigated field experiments

Site	Position	Start	Soil texture	Amount of sludge applied
Lanna	58°21'N, 13°06'E	1997	Silty clay (42 % clay)	8 Mg dry matter ha^{-1} every 2nd yr
Petersborg	55°32'N, 13°00'E	1981	Sandy loam (14 % clay)	4 or 12 Mg dry matter ha^{-1} every 4th yr
Igelösa	55°45'N, 13°18'E	1981	Loam (26 % clay)	4 or 12 Mg dry matter ha^{-1} every 4th yr
Ultuna	59°49'N, 17°39'E	1956	Clay loam (36.5 % clay)	4 Mg C ha^{-1} every 2nd yr

For each experimental treatment, SOC stocks were calculated from i) C concentrations and bulk density measurements for a soil volume corresponding to the mass of minerals to 20 cm depth at the start of the experiment [2], ii) carbon inputs from sludge (Table 2), and iii) carbon inputs from above- and below-ground crop residues that were calculated from crop yields using allometric functions [3].
A single-pool first-order C model (Equation 1) was used for estimating retention (humification) coefficients (H_j) for crop residues and sewage sludge by fitting the following model equation to the final C stocks (C_t) in each treatment:

$$C(t) = \frac{1}{k}\sum_{j=1}^{j=3} HjIj + \left(C(t=0) - \frac{1}{k}\sum_{j=1}^{j=3} HjIj\right)e^{-kt}$$

Eq. 1

where I_j is the C input from the three sources mentioned above and k is the site-specific decomposition rate constant. The values for H_j were estimated simultaneously for all treatments per site by minimizing RMSE using non-linear regression analysis.

Moreover, we compared sludge-C retention in the upper 20 cm, the standard sampling depth in these experiments, with those in the 20-40 cm layer measured in the extreme treatments at two sites. Because the dataset for the 20-40 cm layer was much smaller, we applied a linear SOC balance approach for calculating C retention (total applied sludge-C divided by SOC stock differences between sluge-amended and unamended treatments).

Table 2. Sewage sludge application rates of dry mass, C and N at the four sites. For Igelösa and Petersborg application refers to treatments with high application rates (12 Mg dry matter ha^{-1} every 4th yr.

	DM	C org.	N org.	Min. N	Total N	C/N org.	C/N tot
	---- Mg ha^{-1} yr^{-1} ----		---------------- kg ha^{-1} yr^{-1} --------------				
Lanna	9.22	2.11	135	104	239	15.6	8.8
Igelösa	3.20	0.98	96	42	138	10.2	7.1
Petersborg	3.20	0.98	110	48	158	8.9	6.2
Ultuna	6.24	1.84	164	49	213	11.2	8.6

Results

The estimated retention coefficients H_j for sludge varied between 0.15 and 0.38 at the four sites. Site differences were probably due to sludge quality, which differed between sites and over the years due to changes in processes at the water treatment plants [4, 5]. The performance of the simple model was generally good, yielding low RMSE-values for most sites, which also supports the assumption of linear relationships between crop yields and crop-derived C inputs (Fig. 1).

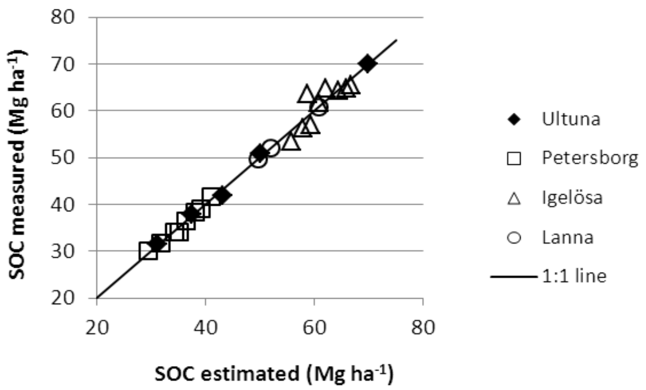

Fig. 1. Measured and estimated (Eq. 1) soil organic carbon stocks in the different treatments at the four sites to a soil depth corresponding to the mass of minerals to 20 cm depth at the start of the experiments.

At Petersborg, carbon concentrations along the soil profile (depth layers 0-22.5, 22.5-25, 25-27.5 and 27.5-30 cm) were significantly higher in the sludge-amended treatment than in the corresponding N fertilized or unfertilized treatments (Fig. 2). Nitrogen fertilization also increased SOC compared to the unfertilized treatment, but the effect was only significant in the upper 27.5 cm of the soil profile.

At Lanna, carbon concentrations along the soil profile (depth layers 0-20, 20-25, 25-50 and 30-40 cm) were significantly higher in the sludge-amended treatment than in N fertilized or unfertilized treatment. Differences between the latter two treatments were not significant.

Treatment effects due to sludge application and N fertilization were similar in the 20-40 cm layer as in the 0-20 cm layer. After 30 years, SOC stocks in the 0-20 cm layer at Petersborg were 2.9

or 4.3 Mg ha^{-1} higher in sludge amended than in unamended treatments in the unfertilized or N fertilized treatment, respectively. Corresponding increases at 20-40 cm depth were 3.4 and 5.7 Mg ha^{-1} (Fig. 3). At Lanna, 13 years of sludge application resulted in 6.0 and 3.8 Mg ha^{-1} higher SOC stocks in the 0-20 and 20-40 cm layer, respectively, than in the N fertilized treatments. The accumulated application rates of carbon in sludge during 30 years at Petersborg and 13 years at Lanna were similar, 29.4 and 27.4 Mg C, respectively (Table 2). Mean accumulation of SOC in the 0-40 cm depth was 8.2 Mg at Petersborg and 9.8 Mg ha^{-1} at the Lanna site in average over N fertilizer rates. Thus, 28 or 36% of accumulated sludge-C input was retained in soil to 40 cm depth at Petersborg and Lanna, respectively. On average, over sites and N fertilization rates, almost half (47%) of the retention of sludge-C occurred in the 20-40 cm layer (Fig. 3). Besides direct retention caused by sludge addition, these estimates also include sludge-induced increased C inputs from crop residues (mainly roots) due to enhanced crop production resulting from sludge-derived nutrients and improved physical soil structure.

Fertilization with N also increased SOC in sludge amended and non-amended treatments. At Petersborg, mean SOC increases due to N fertilization were 5.3 and 4.6 Mg ha^{-1} at 0-20 and 20-40 cm depth, respectively. At Lanna, SOC stocks in the N-fertilized treatments were correspondingly 1.2 and 3.6 Mg ha^{-1} higher than in the unfertilized treatment. Because C/N ratios in sludge were similar to those in soils (about 10), retention of nitrogen was similar to that of carbon.

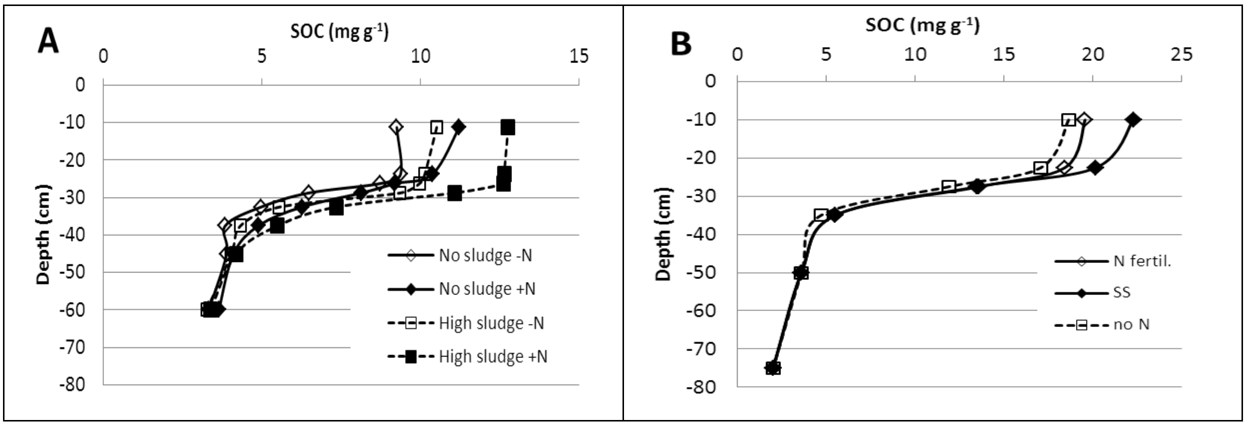

Fig. 2. Soil organic carbon concentrations along the soil profile in sludge-amended treatments versus N fertilized and unfertilized treatments at Petersborg (A) and Lanna (B).

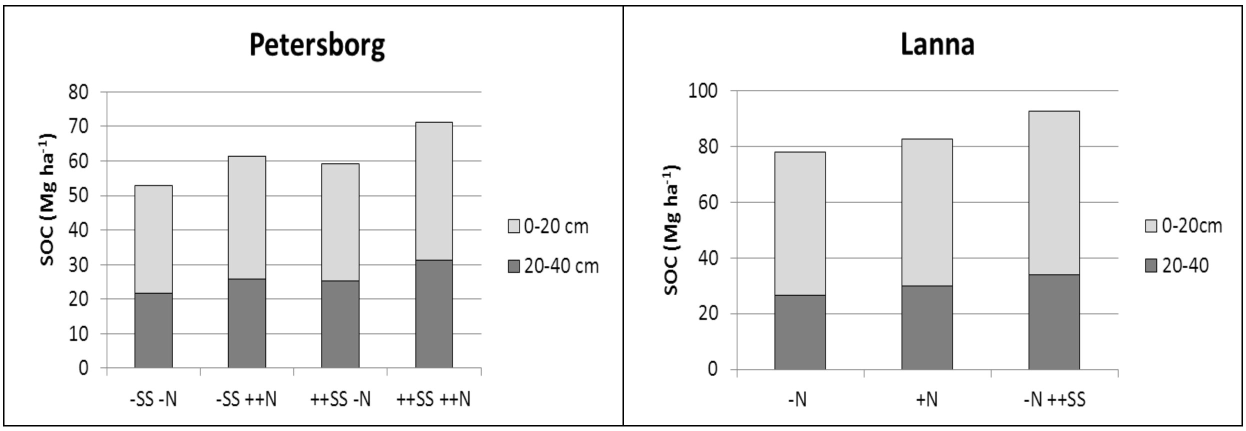

Fig. 3. Soil organic carbon stocks at 0-20 and 20-40 cm depth at Petersborg and Lanna in Sewage sludge-amended treatments (SS) versus N fertilized (+N) and unfertilized treatments (-N).

Conclusion and perspectives

Sewage sludge addition to soil increased SOC directly through C input and indirectly through stimulation of primary production. Between 16 and 32% of C added with sludge additions was retained in the topsoil after 13 to 53 years at the different sites. At the two sites where whole soil profiles were studied, between 28 and 36% of sludge-derived C was retained to 40 cm depth. Since almost 50% of these changes occurred below 20 cm depth and about on third below the Ap-horizon, C changes in upper subsoils need to be considered in soil C balance studies. Indirect positive feedbacks of sludge addition on soil fertility such as an increase in the microbial biomass [5] should also be considered. Nitrogen fertilization had also a considerable positive impact on the carbon balance as shown in previous Swedish studies [2, 6, 7].

References

[1] Kätterer T, Andrén O, 1999. Long-term agricultural field experiments in Northern Europe: Analysis of the influence of management on soil carbon stocks using the ICBM model. Agriculture, Ecosystems and Environment 72, 165-179.
[2] Kätterer T, Bolinder MA, Andrén O, Kirchmann H, Menichetti L, 2011. Roots contribute more to refractory soil organic matter than aboveground crop residues, as revealed by a long-term field experiment. Agriculture, Ecosystems and Environment 141, 184-192.
[3] Bolinder MA, Janzen HH, Gregorich EG, Angers DA, VandenBygaart AJ, 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agriculture, Ecosystems and Environment 118, 29-42.
[4] Peltre C, Christensen BT, Dragon S, Icard C, Kätterer T, Houot S, 2012. Carbon accumulation in soil after repeated applications of different organic amendments evaluated by applying the RothC model to four long-term field experiments. Soil Biology and Biochemistry 52, 49-60.
[5] Börjesson G, Menichetti L, Kirchmann H, Kätterer T, 2012. Soil microbial community structure affected by nitrogen fertilisation and different organic amendments during 53 years. Biology and Fertility of Soils 48, 245–257.
[6] Kirchmann H, Kätterer T, Schön M, Börjesson G, Hamnér K, 2013. Properties of soils in the Swedish long-term fertility experiments: VII. Changes in topsoil and upper subsoil at Örja and Fors after 50 years of nitrogen fertilisation and manure application. Acta Agr. Scand. Section B. 63: 25-36.
[7] Kätterer T, Bolinder MA, Berglund K, Kirchmann H, 2013. Strategies for carbon sequestration in agricultural soils in northern Europe. Acta Agr. Scand. Section A. 00: 00-00.