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SOC sequestration as affected by historic and present management

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ABSTRACT

In 1978, after > 70 years of continuous management of the long-term fertilization experiment in Bad Lauchstädt, a general change of soil management was implemented for several treatments. Experimental plots which had previously received a high input of organic matter (OM) now received only low OM input and vice versa. The resulting changes of SOC concentrations on different treatments vary from -0.1 to $+0.1\,\mathrm{g\,kg^{-1}\,yr^{-1}}$. These trends were analyzed in order to explain the observed variations with the mean carbon input together with the quality of the different sources to build up new SOC. The results showed that this quality related carbon flux from fresh organic matter (FOM) into SOC, here defined as "carbon reproduction flux" (C_{rep}), is a useful indicator to explain changes in SOC trends. Moreover, it can be used to predict the amount of FOM carbon input that is needed to achieve a given sequestration rate. The results revealed that carbon sequestration requires less effort on plots that had already higher carbon input rates in the past because the SOC storage, still far from the equilibrium state, had already a positive trend. Therefore, it is important to consider not only SOC stock but also the direction of the current trend when selecting measures that increase SOC to achieve the goal of the "4‰ Initiative: soils for food security and climate" which was launched during the COP21 conference.

1. Introduction

Soil organic matter, usually characterized by soil organic carbon (SOC), is a component that determines many soil functions (Stockmann et al., 2015). It has come into focus more during the last decade because it represents a major carbon pool in the global carbon cycle. More recently, the option of reducing the CO_2 concentration in the atmosphere by increasing the flux of carbon into the soil was under discussion because soil carbon sequestration in agricultural soils may contribute to mitigate climate change over the next ten to twenty years (Minasny et al., 2017). This raises the question of appropriate management strategies where there is still insufficient knowledge about "both the magnitude and direction of C stock changes in mineral soils associated with land use type, management and other disturbances" as pointed out by Deng et al. (2016).

From the perspective of SOC, management strategies affect SOC related processes i) via the quantity and quality of carbon input (e.g. dead or living plant material, manure) and/or ii) via the quantity of carbon loss, mainly by mineralization but also due to erosion or leaching. On global scale management scenarios can be classified according to their impact on SOC stocks. SOC decrease is mainly initiated by cultivation of natural or semi-natural vegetation (e.g. DeFries et al., 1999; Don et al., 2011; Poeplau et al., 2011). Whereas, SOC increase may be induced by a reduction of tillage intensity of arable soils (Alvarez et al., 2014; Franko and Spiegel, 2016; Prasad et al., 2016) or an increase of carbon inputs e.g. directly by manure and catch crops as well as indirectly by mineral fertilizer, (e.g. Kätterer et al., 2014; Poeplau and Don, 2015; Wei et al., 2016). In this study we focus on the change of fertilization strategy as proxy for a modified carbon input to the soil.

The assessment of the SOC stock in relation to management under practical conditions requires indicators that are easy to apply like the carbon management index (CMI) proposed by Blair et al. (1995) and recently applied by Chaudhary et al. (2017). Although the CMI is aimed at management assessment, it still requires soil analytics to determine SOC in the fertilized treatment and the control treatment. Therefore, we explored other means to describe the accumulation of SOC that relate to management only.

Beside tillage operations, soil management affects the SOC stock mainly from the input of a variety of FOM from crop residues like roots and stubble, crop by-products like straw that may be left on the field and additional organic amendments like manure or compost. All these FOM components are processed by micro- and mesofauna living in the soil. The product of this turnover is usually referred to as soil organic matter, often characterized by SOC. A general problem for the description of SOC dynamics is the quality assessment of different FOM

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sources regarding the formation of new SOC that replaces the decomposed SOC. Models that describe SOC dynamics solve this problem with a classification of the different FOM sources into pools and assigning them characteristic parameters that characterize the turnover time and the amount of carbon that is transferred into CO_2 during this turnover. We describe this continuous process of SOC formation as reproduction and the amount of carbon that is transferred from FOM into SOC per unit of time as carbon reproduction flux C_{rep}. Furthermore, it is hypothesized that this flux can be used as indicator that aggregates the effect of different carbon sources on SOC storage.

For this purpose, a dataset from the "Extended Static Fertilization Experiment" in Bad Lauchstädt (Germany) was analyzed. The special character of this experiment was a management change that, for some treatments, reversed the SOM management after a period of seven decades of continuous fertilization. After the management change, plots that had previously received a high input of FOM received only low FOM input and vice versa. This provided a unique opportunity to analyze the effect of management changes on SOC storage at different SOC levels. We hypothesized that the SOC trend after these modifications can be explained by the average C_{rep} flux before and after this management change. Furthermore, we wanted to use this knowledge to discuss management options on this soil type that would achieve the goal of the 4 per mille initiative for soil carbon accumulation that was launched during the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris (short: COP 21) and is intended to increase soil carbon stocks as compensation for greenhouse gas emissions from anthropogenic sources.

2. Material and methods

2.1. Experiment description

The "Static Fertilization Experiment Bad Lauchstädt" was established in 1902 on a Haplic Chernozem soil in Central Germany. The site conditions were described in detail by Altermann et al. (2005) and experimental details are given by Körschens et al. (1994), Merbach and Körschens (2002) and Merbach and Schulz (2013).

The crop rotation in this experiment consisted of sugar beet (*Beta vulgaris*) – spring barley (*Hordeum vulgare*) – potatoes (*Solanum tuberosum*) – winter wheat (*Triticum aestivum*); one of these crops was grown per year. The experimental factors were organic and mineral fertilization. Further on, we will refer to the treatments with an organic amendment of farmyard manure with the application rates (as fresh matter) "without" and "with 15 Mg ha^{-1} yr^{-1}", abbreviated here as M_0 and M_1, respectively. The manure was applied every second year to the root crops in doubled doses. These manure treatments were orthogonally combined with two NPK fertilization levels "without" and "with NPK", here abbreviated as NPK_0 and NPK_1, respectively. The NPK doses depended on the crop as well as the amount of applied manure and were adapted over time according to the productivity of the grown varieties. After harvest, the sugar beet leaves, as well as straw were removed from the plots.

In 1978, after a period of > 70 years, creating the "Extended Static Fertilization Experiment", the management of the above mentioned treatments was changed. On each of them, an orthogonal combination of two manure doses equal to the previous application rates M_0 and M_1 was implemented, with three levels of mineral nitrogen fertilization "without N", "normal" and "high"; here abbreviated as N_0, N_2 and N_4, respectively. The resulting plot size after this transformation is 55 m^2. Consequently, after the management change the new experimental design consists of three experimental factors: manure application, mineral nitrogen fertilization, and initial SOC amount according to the four different levels caused by the previous management. In Fig. 1 is shown a schematic diagram that illustrates the impact of the different experimental factors on trends of the SOC concentrations for the time before and after management change including the corresponding treatment abbreviations following the style $M_iNPK_j \rightarrow M_iN_k$ with an arrow separating the management before and after change.

For the characterization of the carbon input in the period before the management change, we used the crop yields from 1956 to 1978 of the appropriate plots together with the manure application rate. Regarding the treatments after management change as shown in Fig. 1, yield and SOC data from 1979 (first harvest after management change) to 2010 (representing 8 rotations) were processed. The SOC dynamics was described as a linear trend where the linearity for the chosen time interval was confirmed statistically by comparing the Akaike information criterion as provided by the R system (R Core Team, 2016) for a linear approach and a second order polynomial.

2.2. SOC data

In this study, we used SOC data determined after the management change. Soil samples were taken annually after harvest of the crop. There are data gaps in 1993 for all plots with manure application and in 1998 for the plots with a M_0NPK_0 history. Sampling was completely skipped in the years 1997, 1999, 2001, 2003 and 2005. In all cases, a composite sample was mixed from 20 subsamples taken with an auger from the upper soil layer (0–20 cm). After sieving to < 2 mm and air-drying, SOC was determined by dry combustion at 950 °C in a stream of oxygen. Carbonate concentration of the soil was negligible. Therefore, the measured total C concentration was considered as SOC.

2.3. Yield data

We used the average crop yields (grain, tuber or beet) for each treatment before (1956–1978) and after (1979–2010) management change as shown in Fig. 2 to calculate the contribution of crops to the carbon input to the soil organic matter.

2.4. Assessment of soil management change

The C input with FOM consists only of the applied manure, as well as crop roots and stubbles because straw and beet leaves were removed at harvest.

The amount of carbon that is available to replace mineralized SOC was calculated basing on the approach used by Franko et al. (2011) to model SOC dynamics for a set of long term experiments with different crop rotations with the Candy Carbon Balance model (CCB). From the CCB model, we took the parameters that describe the amount of FOM from roots and stubbles in relation to the yield of the main product as well as the partitioning between FOM transfer into SOC and CO_2. The average annual carbon input by manure was calculated to be 2968 kg ha^{-1} yr^{-1} which represents a C_{rep} flux of 1899 kg ha^{-1} yr^{-1}. The crop based C_{rep} flux was calculated with Eq. (1) where the parameter η_i represents the part of FOM carbon that is incorporated into SOC. We calculated C_{rep} before and after management change as average value using the observed yields of the four crops (sugar beet, spring barley, potato, and winter wheat) as well as the parameters shown in Table 1.

$$\mathrm{C_{rep}} = \frac{1}{n}\cdot\sum_{i=1}^{n}\left(\left(K_i + F_i\cdot\frac{1}{N}\cdot\sum_{j=1}^{N}Y_{i,j}\right)\cdot\eta_i\right) \tag{1}$$

with

K_i, F_i: parameters to calculate the amount of FOM carbon from the crop yield for crop i (see Table 1),

$Y_{i,j}$: yield of crop i in year j in Mg ha^{-1},

N: Number of years to calculate the yield average,

n: Number of crops in the crop rotation.

The dynamics of total SOC is a long-term process following a non-linear time course. If this long-term course is divided into several shorter periods, the SOC dynamics of each period can be assumed to be