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Soil carbon dynamics estimation and dependence on farming system in a temperate climate

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ABSTRACT

Maintaining or enhancing the stock of soil organic carbon (SOC) is a key factor in sustaining the soil resources of the world. The objective of this research was to study the effect of different farming systems (conventional farming with mineral fertilizers and crop specific fertilization vs. organic farming with organic fertilizers (catch crops and composted manure)) under the same 5-crop rotation (red clover, winter wheat, pea, potato, barley undersown with red clover) system on the SOC stock and the stability of SOC. The second aim was to quantify plant C inputs to the soil and to identify the relationship between C sequestration rate and C input. Data presented in this paper concerned the first rotation during 2008–2012. The main factors were farming systems: conventional and organic. Four conventional farming systems differed in the mineral nitrogen application rates used. In two organic farming systems catch crops were used with or without composted solid cattle manure. The SOC stock was determined before experiment establishment and after the first rotation. The C input into the soil was calculated based on the main product yield. The stock of SOC increased (2.57 Mg ha^{-1} y^{-1}) considerably after the first rotation only in the organic farming systems, where the total C inputs were 1368 kg C ha^{-1} y^{-1} higher compared to the average C inputs in conventional systems. The mineral N rate did not influence the C-input but it had an effect on the properties and mineralisation of soil organic matter. The stable C fraction of SOC proportion increased in the system in which the highest rate of mineral N (20–150 kg N ha^{-1}y^{-1} depending on crop) was used and its proportion in the soil was comparable with the results obtained from organic farming systems. Thus, the intensive management with high N rates may benefit to a formation of more stabile SOC if the crop rotation used is properly elaborated.

1. Introduction

Soil organic carbon (SOC) plays an important role in nutrient cycling and improving soil physical, chemical and biological properties (Manna et al., 2007). In addition to promoting the ability of soil to produce food it reduces the concentration of CO_2 in the atmosphere by increasing SOC stock (Lal, 2011) and thereby stabilizes and enhances natural ecosystems (Gregorich et al., 1994). The sustainability of agricultural systems with reduced emissions of greenhouse gases has become an important issue all over the world. Depending upon the agricultural management practices applied, the soil can serve both as a source or sink for atmospheric CO_2 (Lal, 2004; Wilson and Al-Kaisi, 2008). The stock of SOC reflects the net balance between ongoing accumulation and

Abbreviations: C, carbon; BD, bulk density; BD_{calc}, calculated bulk density; BD_{meas}, measured bulk density; CC, catch crop; DM, dry matter; DOC, dissolved organic carbon; DOCp, the proportion of soil dissolved organic carbon of the total organic carbon; HI, harvest index; N0, control system (with no additional fertilizers used); N1N2N3, systems with different N rates used depending on crop; NPP, net primary productivity; N_{tot}, total nitrogen; O + CC, farming system with catch crops; O + CC + M, farming systems with catch crops and composted manure; SOC, soil organic carbon; SOM, soil organic matter; C_P, carbon of the agricultural product removed from the field; C_S, carbon in shoot; C_R, carbon in root; C_E, carbon in rhizodeposition; S/R, shoot/root ratio; Y_P, DM yield of the agricultural products.

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decomposition processes, which are influenced by both crop productivity and field management (Carter et al., 1997). In any system where C input to the soil exceeds the C output from the soil, a positive imbalance occurs, which subsequently results in sequestration of C in the soil (Jastrow et al., 2007). Estimation of soil C sequestration requires quantification of the rates of C inputs and releases under changed soil management.

In general, agricultural utilization of soils has been found to decrease their SOC content (Dalal and Mayer, 1986; Saviozzi et al., 1994; Blair, 2000) through disruption of the equilibrium between the competing processes of humus formation and mineralization. Management practices like proper cropping systems and balanced fertilization are believed to offer the greatest potential for increasing SOC stock in agricultural soil (Paustian et al., 1997; West and Post, 2002; Lal, 2004). To characterize, predict and manage soil C dynamics, we need precise and accurate estimates of C inputs to the soil (Bolinder et al., 2007). Predicting the changes in soil C stocks depends on net primary productivity (NPP) and the proportion of the NPP returned to the soil (Paustian et al., 1997; Bolinder et al., 2006; Koga and Tsuji, 2009). Thus crop residues, plant roots and also organic amendments represent a significant source of inputs for soil C sequestration (Koga and Tsuji, 2009). Changes in inputs, such as fertilizers and residues (Janzen 1987; Campbell et al., 1991), which regulate soil microbial activity and mineralization rates, will ultimately be reflected in the SOC content (Gregorich et al., 1994). Generally, it is found that addition of organic fertilizers with or without mineral fertilizer increases the SOC content (Blair, 2000; Blair et al., 2006). Inorganic fertilizers influence SOC concentration indirectly by increasing crop yields and thereby increasing the return of crop residues to the soil (Liang et al., 2012). It is assumed that crop productivity is positively related to C amount released into the soil (Wilson and Al-Kaisi, 2008). The effects of the application of mineral fertilizers on SOC content have been contradictory: some have found SOC content increase (Campbell and Zentner, 1993; Gong et al., 2009), but others no influence on SOC content (Halvorson et al., 2002).

Previous and present soil and crop management practices determine existing SOC levels to a large extent and will also influence future SOC stock (Kätterer et al., 2008). Changes in SOC due to management practices are difficult to quantify as they occur slowly (Paustian et al., 1997) due to the high background levels of SOC and natural soil variability (Haynes, 2005). Thus, SOC is not sensitive to short-term soil quality changes with different soil or crop management practices. The use of soil organic matter (SOM) chemical fractions to evaluate changes in soil C dynamics due to the agricultural use is more effective than the determination of the total SOM (Guimaraes et al., 2013). According to Ruhlmann (1999) SOM is divided into two pools with different resistance to decomposition: (i) a small C pool with rapid (few decades) turnover time (dynamic, active, labile pool), which includes easily decomposable organic matter (e.g., microbial biomass) and (ii) a large C pool with slow (centuries to millennia) turnover time (stable, passive pool). The turnover of labile C pools influences crop productivity by regulating nutrient availability and cycling in the soil (Janzen, 2004). It is a primary source of mineralisable N, S, and P (Haynes, 2000). The content of dissolved organic C (DOC) is much more sensitive to change in soil management practices (Saviozzi et al., 2001; Xu et al., 2011), due to its rapid response to changes in soil C supply. Its use as an early indicator of the impact of land use on SOC quality has been suggested (Gregorich et al., 1994). The DOC fraction is a suitable soil quality indicator for describing the balance between the amount of labile C input into the soil and its durability and decomposition in the soil (Gregorich and Janzen, 1995). The content of DOC in the soils depend on both cropping intensity, which influences the quantity and quality of crop residues, and on tillage, which impacts residue placement in the soils. In the long term, vegetation type and the quantity of organic residues have been shown to be the primary factors influencing the amount and composition of DOC (Chantigny, 2003). Lundquist et al. (1999) found twice as much soil DOC under crops that produce more residues. He also showed that the labile C fraction is greater with organic farming than with conventional farming.

Although the major goal of any agricultural management strategy is to enhance crop yield, environmental sustainability must be major issue for the long-term stability of agroecosystems (Singh et al., 2009). Thus, improved agronomic practices that could lead to reduced carbon losses or even increased SOC storage are highly desirable (Gattinger et al., 2012).

As crop type and agronomic practices such as tillage, fertilization and application of organic amendments influence plant biomass production (Kundu et al., 2007), it is essential to understand how crop residue biomass production is influenced by different field management practices, which vary with soil type, climate, and crop rotation and how this impacts soil C sequestration (Koga and Tsuji, 2009). Therefore, it is important to assess C sequestration potential for specific climate/soil/crop systems in order to draw site-specific conclusions.

The aim of this research was to study the effect of different farming systems (conventional farming with mineral fertilizers vs. organic farming with organic fertilizers (catch crop (CC) and composted manure)) under the same crop rotation on the SOC stock. The second aim of the study was to quantify crop-specific C inputs and to identify the relationship between C sequestration and C input into the soil. We hypothesised that it is not possible to predict SOC dynamics based on the amount of C input. Different management techniques impact the properties of C input and the conditions of its mineralisation. Therefore, higher C input into the soil may not necessarily lead to higher SOC accumulation and cause higher SOC stability.

2. Material and methods

2.1. Field experiment

The field experiment was situated at the experimental station of the Estonian University of Life Sciences in Eerika, Tartu, Estonia (58° 22′N, 26° 40′E). In 2008 a crop rotation experiment with two organic and four conventional farming systems was established. The experiment was set up in four replications with each plot (60 m^{-2}) in a systematic block design. Randomisation was fixed in every year in all farming systems and replications. Each plot was 6 m wide and 10 m long. Organic and conventional plots were separated with a 18 m long section of mixed grasses to avoid contamination with synthetic pesticides, mineral fertilizers and CC. Between organic systems there was also a 10 m long protective area for preventing the spread of cattle manure to plots where manure was not used. Conventional systems and all four replications were next to each other without separation. Between the conventional systems there was a transition area (1 m long and 6 m wide), where no samples were taken. The soil of the experimental field is *Stagnic Luvisol* according to the World Reference Base classification (FAO, 2006). The texture of the soil is sandy loam (56.5% sand, 34% silt and 9.5% clay) for the epipedon with a humus layer of 20–30 cm (Reintam and Köster, 2006). At the beginning of the experiment the soil humus layer characteristics were as follows: pH_{KCl} 5.9, 13.8 mg C_{org} g^{-1}, 1.4 mg N_{tot} g^{-1}, plant available P, K, Ca and Mg contents were 112.6 mg P kg^{-1}, 168.1 mg K kg^{-1}, 1185 mg Ca kg^{-1}, 188.7 Mg mg kg^{-1}, respectively. Plant available nutrients were determined by the ammonium lactate (AL) method (Egnér et al., 1960). A more detailed description of the experiment is presented in Tein et al. (2014).