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Research paper

Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain

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ABSTRACT

To improve C sequestration in soils and mitigate climate change, it is essential to understand how nutrient management strategies impact on soil organic carbon (SOC) stocks and labile fractions. This study was designed to explore changes in soil bulk density (BD), SOC concentrations, SOC stocks and soil labile organic C fractions (mineralizable C (Cmin), microbial biomass C (MBC), dissolved organic C (DOC), particulate organic C (POC), light fraction organic C (LFOC) and permanganate oxidizable C ($KMnO_4$-C)) under 26-year fertilization regimes in a wheat-maize rotation system in the North China Plain. Soil from the following six treatments was analyzed: (1) Control with no amendment addition (CK); (2) Standard rate of mineral fertilizer treatment (SMF) reflecting local farmers' practice; (3) Standard rate of organic manure treatment (SMA) with total N input equal to SMF; (4) Half the standard rate of mineral fertilizer plus half the standard rate of organic manure treatment (1/2 SMF + 1/2 SMA); (5) Double standard rate of mineral fertilizer treatment (DMF); (6) Double standard rate of organic manure treatment (DMA). Results showed that all long-term fertilization regimes significantly decreased BD in topsoil compared to CK except for SMF, with treatments that included organic manure resulting in the lowest BDs. Treatments that included organic manure had significantly higher SOC concentrations and stocks than mineral or unfertilized treatments. The organic manure treatments also had higher concentrations of non-labile C but at the same time a higher proportion of labile C than the mineral or unfertilized treatments. This was confirmed by the carbon management index (CMI) which was significantly increased by organic manure addition. Control and mineral fertilized treatments had higher efficiencies of C retention (RE) from added inputs (crop residues only). Differences in Cmin, POC and $KMnO_4$-C were affected by differences in MA-C, however, changes in rhizodeposition-C, stubble-C and root-C significantly affected DOC, MBC and LFOC. This study demonstrates that fertilization strategies that include organic manure can increase the pool of stable C in the surface soil layer, while at the same time increasing concentrations and proportions of labile C. Organic manure use can therefore contribute to improved nutrient cycling services and higher soil quality in the North China Plain.

1. Introduction

The accumulation of carbon (C) in soils is a function of the relationship between C inputs in the form of crop residues and organic fertilizers, and the rate of soil C breakdown (decomposition) as mediated by soil microorganisms and the environment (soil type, temperature) (Cooper et al., 2011). Regular inputs of residues, compost, or manure can increase total soil organic C (SOC) until it reaches a higher

Abbreviations: BD, bulk density; SOC, soil organic carbon; MBC, microbial biomass carbon; DOC, dissolved organic carbon; POC, particulate organic carbon; $KMnO_4$-C, permanganate oxidizable carbon; NCP, North China Plain; L, lability; LI, lability index; CPI, carbon pool index; CMI, carbon management index; RE, retention efficiency

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equilibrium level, related to the balance between C inputs and decomposition processes. This equilibrium level is also affected by the types of C inputs to the system and how these are converted into stable C in the soil by microbial communities (Kallenbach et al., 2016). Crop residues may be relatively labile and not increase levels of stable C in the soil, while materials like biochar are recalcitrant and can have a much longer half-life in the soil (Lorenz et al., 2007; Steinbeiss et al., 2009). The impacts of historic additions of different quantities and qualities of C inputs have been observed in long-term organic matter addition experiments including the Broadbalk Experiment at Rothamsted, UK (Blair et al., 2006a), the DOK trial in Switzerland (Mäder et al., 2002) and various experiments in China (Cai and Qin 2006; Lou et al., 2011; Ding et al., 2012; Yang et al., 2012; Liu et al., 2013).

SOC is recognized as vital for the delivery of multiple ecosystem services including not only climate regulation i.e. soil C sequestration (Plaza-Bonilla et al., 2014), but also the supporting service of nutrient cycling (Duru et al., 2015). However, the properties of the SOC pool required for these two ecosystem services may not be the same. For soil C to contribute to climate regulation by sequestration, it needs to be in a stable, non-labile form that will not be susceptible to losses should the system be perturbed by a change in tillage (Powlson et al., 2012), small changes in C inputs (Liu et al., 2013), or by climatic changes that increase microbial activity e.g. rising temperatures (Lal, 2004).

Soil C pools that promote microbial activity and nutrient cycling are primarily the labile pools (Kaye and Hart, 1997), a series of small, but variable, proportions of SOC with turnover times of a few days to months. These pools have been suggested as early sensitive indicators of soil quality which influence soil function in specific ways (Cambardella et al., 1998; Yang et al., 2005; Rudrappa et al., 2006; Xu et al., 2011; Blanco-Moure et al., 2016). Various techniques are used to estimate the size of the labile C pools. Cmin, which is biologically respired CO_2, indicates the total metabolic activity of the heterotrophic microorganisms in the soil that are decomposing organic matter (Haynes, 2005). Accurate identification of the mineralizable C pool is essential for modelling soil C dynamics and ecosystem responses to changing environmental factors (Saviozzi et al., 2014). POC and LFOC obtained by particle size or density fractionation methods have been used to identify the effects of fertilization practices on soil organic matter in many studies (Wander, 2004). The POC and LFOC concentrations have been found to be elevated in farming systems relying on organic fertility compared with those using synthetic fertilizers (Wander et al., 1994; Fortuna et al., 2003; Nissen and Wander, 2003). Dissolved organic C can be extracted using a weak salt solution (Jensen et al., 1997), and is a measure of carbon easily transportable within ecosystems and the formation of SOC (Neff and Asner, 2001). Organic matter (organic manure or crop residues) additions to soil over time have been demonstrated to increase DOC contents (Gong et al., 2009a; Xu et al., 2011; Liu et al., 2013, 2015). Microbial biomass measurement, particularly MBC, which serves as a sink for labile nutrients or a source of nutrients for biota, has been extensively used to assess soil fertility under long-term fertilization regimes (Li et al., 2008, 2013). $KMnO_4$-C, the fraction of labile C which is obtained from chemical oxidation methods using $KMnO_4$ (Blair et al., 1995), has since been considered as an early sensitive index for the impacts of long-term applications of fertilizers or organic resources on the dynamics of the active SOC fraction (Mtambanengwe and Mapfumo, 2008; Xu et al., 2011).

Non-labile C can be estimated as the difference between SOC and $KMnO_4$-C (Blair et al., 2006a). The Carbon Management Index (CMI) can be calculated to give an indication of the changes in the C dynamics of each system and ecosystem response relative to a paired reference soil (Blair et al., 1995). The CMI increases when either or both the treatment total C or labile C increase as a proportion of the reference. The CMI can also be a useful parameter for assessing the potential of long-term manure addition, straw incorporation or conservation agriculture to improve soil quality and thus optimizing practices that impede soil degradation (Xu et al., 2011; Wang et al., 2015a; Ghosh et al., 2016).

The North China Plain (NCP) region, referred to as "China's breadbasket" is a highly productive agricultural area with the main cropping system of a winter wheat-summer maize double-cropping rotation. It is essential to optimize fertilization to maintain crop yields while reducing negative impacts on environment in this region with many researchers focusing on this challenge (Chen et al., 2014). Lin et al. (2009) showed that substituting 100% or 50% of mineral fertilizers with organic manure over 15 years could maintain crop yields and increase SOC compared to equivalent mineral fertilizer treatments in a trial in the NCP region. However it is currently still not known how the different fertilizer treatments in this trial have affected soil labile and non-labile organic C fractions under the 26-year fertilization regimes. Therefore, this study was conducted to investigate how different fertilizer treatments over the 26 year experiment had impacted on the proportions of labile (Cmin, MBC, DOC, POC, LFOC and $KMnO_4$-C) and non-labile C fractions in each treatment.

2. Materials and methods

2.1. Site description and experimental design

This study was carried out on a long-term fertilization experiment started in 1986 at Dezhou Experimental Station (116°34′E, 36°50′N, altitude: 20 m), Chinese Academy of Agricultural Sciences (CAAS), Yucheng, Shandong, China. The full site description and experimental design are described in Li et al. (2015). Briefly, this region belongs to a semi-humid warm temperate continental monsoon climate zone with an average annual temperature of 13.4 °C. The annual average sunshine period is 2640 h and the annual average period free of frost is 206 days. The mean annual precipitation is 569.6 mm, and more than 70% of the rainfall falls between June and September. The soil is a Fluvo-aquic type formed from the sediments of the Yellow River with light loam texture (clay 21.4%; silt 65.6%; sand 13.0%). Soil initial chemical properties prior to the beginning of the experiment in 1986 were 3.93 g total soil organic carbon kg^{-1}, 0.51 g total nitrogen kg^{-1}, 7.50 mg Olsen P kg^{-1}, 73.00 mg ammonium acetate-extractable K kg^{-1} and 0.96 g soluble salt kg^{-1}. The experiment mimics the standard winter wheat-summer maize double cropping system which is widely used in the NCP. Standard commercial tillage and irrigation regimes are used.

Six treatments are arranged in a randomized complete block design with four replications (total 24 plots). Each plot is 28 m^2 (4 m × 7 m) with a 0.8 m concrete slab separating the plots. The six treatments are: (1) Control with no amendment addition (CK); (2) Standard rate of mineral fertilizer treatment (SMF) that reflects local farmers' practice; (3) Standard rate of organic manure treatment (SMA) with N input rate equal to SMF; (4) Half the standard rate of mineral fertilizer plus half the standard rate of organic manure treatment (1/2 SMF + 1/2 SMA); (5) Double standard rate of mineral fertilizer treatment (DMF); (6) Double standard rate of organic manure treatment (DMA). The organic manure is cattle manure from the dairy industry nearby and it is composted by regular turning (3–4 times) over a 4 month period before application. Typical compost nutrient concentrations are 1.00–1.84% N, 0.58–1.02% P_2O_5 and 0.98–1.15% K_2O. All N (mineral fertilizer or cattle manure) application rates are based on total N contents. Fertilizer N, P and K sources are urea (47% N), mono-calcium phosphate (17% P_2O_5) and potassium sulphate (50% K_2O) with the standard application rates of 375–450 kg N ha^{-1}, 225–300 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1} per year, respectively. Organic manure and total mineral fertilizer P and K are applied once before winter wheat sowing. Total mineral fertilizer N is applied twice per year: half is applied in October before winter wheat sowing and the other half is applied in June before summer maize sowing. For winter wheat, the N application is split with 40% N applied before sowing and 60% N applied to the soil surface between the rows at jointing stage of winter wheat. For summer maize, 40% N is applied before sowing, and 60% N is applied to the soil

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