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Effects of enhancing soil organic carbon sequestration in the topsoil by fertilization on crop productivity and stability: Evidence from long-term experiments with wheat-maize cropping systems in China

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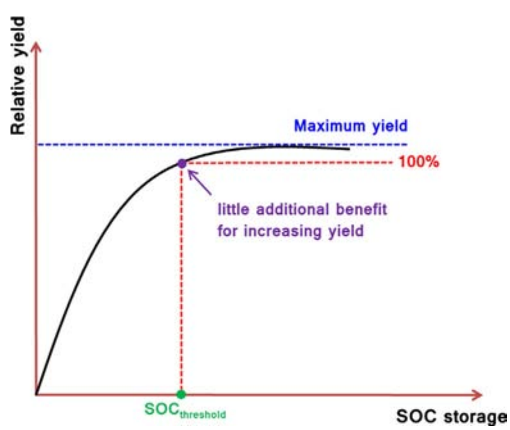
HIGHLIGHTS

- 7.4-13.1% of total C input over 20-30 years was accumulated to the topsoil
- SOC slightly and positively impacted crop yield and its stability in Northern China.
- SOC significantly improved crop yield and its stability in Southern China.
- Benefits of SOC increase on yields reach ~35 Mg C ha^{-1} of SOC in the Southern China.

GRAPHICAL ABSTRACT



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ABSTRACT

Although organic carbon sequestration in agricultural soils has been recommended as a 'win-win strategy' for mitigating climate change and ensuring food security, great uncertainty still remains in identifying the relationships between soil organic carbon (SOC) sequestration and crop productivity. Using data from 17 long-term experiments in China we determined the effects of fertilization strategies on SOC stocks at 0–20 cm depth in the North, North East, North West and South. The impacts of changes in topsoil SOC stocks on the yield and yield stability of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were determined. Results showed that application of inorganic fertilizers (NPK) plus animal manure over 20–30 years significantly increased SOC stocks to 20-cm depth by 32–87% whilst NPK plus wheat/maize straw application increased it by 26–38% compared to controls. The efficiency of SOC sequestration differed between regions with 7.4–13.1% of annual C input into the topsoil being retained as SOC over the study periods. In the northern regions, application of manure had little additional effect on yield compared to NPK over a wide range of topsoil SOC stocks (18–>50 Mg C ha^{-1}). In

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the South, average yield from manure applied treatments was 2.5 times greater than that from NPK treatments. Moreover, the yield with NPK plus manure increased until SOC stocks (20-cm depth) increased to ~35 Mg C ha^{-1}. In the northern regions, yield stability was not increased by application of NPK plus manure compared to NPK, whereas in the South there was a significant improvement. We conclude that manure application and straw incorporation could potentially lead to SOC sequestration in topsoil in China, but beneficial effects of this increase in SOC stocks to 20-cm depth on crop yield and yield stability may only be achieved in the South.

1. Introduction

Soil organic carbon (SOC) can play an important role in increasing crop productivity, improving soil fertility (Tiessen et al., 1994), reducing atmospheric carbon dioxide (CO_2) enrichment (Lal, 2004), and providing other ecosystem services, such as improved soil structure and water retention (Fan et al., 2013a). Low SOC stocks could reduce crop yield through effects on soil fertility and significant nutrient loss may also occur as a result of low nutrient buffer or retention capacity. Changes in SOC stocks have been reported extensively on the global (FAO, 2001), regional (Huang and Sun, 2006; Smith, 2004) and plot scales (Zhang et al., 2010), which suggests that society has paid increasing attention to the potential for sequestering organic carbon in soils in an effort to mitigate climate change and promote crop productivity. For example, it has been reported that a 1% increase in SOC content of the topsoil (0–20 cm) could increase cereal yield by 430 kg ha^{-1} and reduce yield variability by 3.5% (Pan et al., 2009). However, others have argued that claims about the potential benefits of increasing C inputs to the soil must be made with caution because of the uncertainties regarding how much can be sequestered under different climates and soil types (Brock et al., 2011; Manlay et al., 2007; Seremesic et al., 2011). Therefore, it is imperative to quantify the relationships between C inputs, SOC sequestration and crop productivity.

In the last three decades, China has been facing a challenge to ensure crop production is increased while mitigating greenhouse gas (GHG) emissions. China uses only 7% of the world's arable land to feed 22% of the global population (Fan et al., 2010) and produces over 20% and 17% of the world's maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) grain, respectively (FAO, 2010). If China intends to maintain the policy of grain self-sufficiency, crop productivity has to be increased without reducing soil fertility including SOC content, one of the indicators for ensuring crop production (D'Hose et al., 2014). Currently, the average SOC concentration in the root zone of croplands (about 10 g C kg^{-1}) in China is much lower than that (25–40 g C kg^{-1}) in Europe and the United States (Fan et al., 2010). Furthermore, SOC losses from China's croplands have been widely reported (Huang and Sun, 2006; Qin et al., 2013; Sun et al., 2010). SOC stocks of agro-ecosystems may be increased by improving agronomic practices. Applications of animal manure and the incorporation of straw in the soil are recognized as SOC-enhancing management options (Lu et al., 2009; Tian et al., 2015). It has been reported that SOC stocks in the top 20 cm of the world's soils increased by 0.24–0.46 Mg C ha^{-1} year^{-1} with a decade of manure application (Gattinger et al., 2012). In addition, it was reported that in Southern China SOC in the topsoil (0–20 cm) increased by 3.8 Mg C ha^{-1} following manure application for 22 years compared with soils receiving mineral fertilizers alone (Huang et al., 2010). It has also been estimated that an additional 3.8 Tg C year^{-1} could be sequestered in soil if all of the straw generated from arable fields in China were returned to the soils (Lu et al., 2009).

It is challenging to quantify the contribution of SOC to either maintaining or stabilizing crop yield, as the contribution could be concealed by other factors given the complex interactions that occur between soil, root systems and canopies (Bingham, 2001). Most studies conducted across the world have suggested that there is some linear relationship between SOC stocks in the root zone and crop yield and its stability (Bauer and Black, 1994; Beyer et al., 1999; Lal, 2010; Smith, 2004). However, a significant non-linear relationship has been reported between relative crop yield and SOC in the root zone (Lal, 2009), which implies that there is an upper value of SOC stocks in the root zone beyond which there will be no additional benefit on crop yield of increasing SOC stocks (Loveland and Webb, 2003; Krull et al., 2004). For example, crop yields did not increase any further when SOC content in the topsoil exceeded 2% in the upland soils of Alberta, Canada (Krull et al., 2004). Moreover there could be potential hazards of adding too much C to soils, such as surface crusting, increased detachment by raindrops, decreased hydraulic conductivity (Haynes and Naidu, 1998) and water-repellency (Olsen et al., 1970). Addition of excessive amounts organic materials to soils could also lead to losses in soil nitrogen (N) and/or phosphorus (P), resulting in surface and ground-water pollution (Patrick et al., 2013).

Determining the upper value of SOC stocks would provide guidance for designing management practices to optimise crop yields and mitigate climate change. However, there are few studies to date that have examined the relationship between SOC stocks and crop productivity, and quantified the maximal yield-responsive SOC stocks based on long-term observations (Lal, 2006, 2010). The objective of this research was to analyse datasets from 17 long-term fertilization experiments across China to: 1) determine the impact of different fertilizer application and straw management strategies on SOC sequestration in topsoil (0–20 cm) in different regions; 2) to establish the relationships between SOC stocks to 20-cm depth and crop yield and yield stability for the different regions; and 3) to determine whether the maximal yield-responsive SOC stocks for enhancing cereal yields differs between regions. The overall aim of the research was to establish whether soil management practices to optimise yield and yield stability should be modified for specific regions.

2. Methods and materials

2.1. Long-term fertilization experiments

Datasets collected at 17 long-term fertilization experiments established between 1979 and 1990 in arable lands across China were used for this study (Fig. 1 and Table S1). Four sites were located in the North East region: Haerbin (HEB), Gongzhuling (GZL-A and -B), and Shenyang (SY); four in the Northwest region: Urumqi (UM), Zhangye (ZY), Pingliang (PL) and Yangling (YL); five in the North region: Changping (CP), Tianjin (TJ), Yucheng (YC), Zhengzhou (ZZ) and Xuzhou (XZ); and four in the South region: Suining (SN), Chongqing (CQ), Qiyang (QY) and Jinxian (JX).

Climatic conditions, and soil properties at the beginning of the experiments are presented in Tables S1 and S2. Various climatic types are represented in these regions. Annual average temperatures varied from 3.5 °C at the HEB site to 18.3 °C at the CQ site. Annual precipitation ranged from 127 mm at the ZY site (in the arid area) to 1581 mm at the JX site in the humid monsoon climate zone. Annual pan evaporation varied from 990 mm at the CQ site to 2570 mm at the UM site (data from China meteorological sharing service system, http://cdc.cma.gov.cn/). Annual evaporation at the sites in the South region was almost the same as annual precipitation. However, it was much higher than annual precipitation in the other regions (Table S1). Irrigation was applied at the majority of sites in the North and North West (Table S1).