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Carbon sequestration in an intensively cultivated sandy loam soil in the North China Plain as affected by compost and inorganic fertilizer application

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ABSTRACT

Understanding the balance between soil organic carbon (SOC) accumulation and depletion under different fertilization regimes is important for improving soil quality and crop productivity and for mitigating climate change. A long-term field experiment established in 1989 was used to monitor the influence of organic and inorganic fertilizers on the SOC stock in a soil depth of 0–60 cm under an intensive wheat–maize cropping system in the North China Plain. The study involved seven treatments with four replicates: CM, compost; HCM, half compost nitrogen (N) plus half fertilizer N; NPK, fertilizer N, phosphorus (P), and potassium (K); NP, fertilizer N and P; NK, fertilizer N and K; PK, fertilizer P and K; and CK, control without fertilization. Soil samples were collected and analyzed for SOC content in the 0–20 cm layer each year and in the 20–40 cm and 40–60 cm layers every five years. The SOC stock in the 0–60 cm depth displayed a net decrease over 20 years under treatments without fertilizer P or N, and in contrast, increased by proportions ranging from 3.7% to 31.1% under the addition of compost and fertilizer N and P. The stabilization rate of exogenous organic carbon (C) into SOC was only 1.5% in NPK-treated soil but amounted to 8.7% to 14.1% in compost-amended soils (CM and HCM). The total quantities of sequestered SOC were linearly related ($P < 0.01$) to cumulative C inputs to the soil, and a critical input amount of 2.04 Mg C ha^{-1} yr^{-1} was found to be required to maintain the SOC stock level (zero change due to cropping). However, the organic C sequestration rate in the 0–60 cm depth decreased from 0.41 to 0.29 Mg C ha^{-1} yr^{-1} for HCM and from 0.90 to 0.29 Mg C ha^{-1} yr^{-1} for CM from the period of 1989–1994 to the period of 2004–2009, indicating that the SOC stock was getting to saturation after the long-term application of compost. The estimated SOC saturation level in the 0–60 cm depth for CM was 61.31 Mg C ha^{-1}, which was 1.52 and 1.14 times the levels for NPK and HCM, respectively. These results show that SOC sequestration in the North China Plain may mainly depend on the application of organic fertilizer. Furthermore, the SOC sequestration potential in the 0–20 cm layer accounted for 40.3% to 44.6% of the total amount in the 0–60 cm depth for NPK, HCM, and CM, indicating that the SOC sequestration potential would be underestimated using topsoil only and that improving the depth distribution may be a practical way to achieve C sequestration.

1. Introduction

The dynamics of soil organic carbon (SOC) stocks and the role that the soil may play in the long-term accumulation and sequestration of atmospheric CO_2 are of great concern because of their impacts on the mitigation of climate change, the sustainability of crop productivity, and soil fertility (Kirchmann et al., 2004; Srinivasarao et al., 2012). In cropland, a high SOC level can be achieved through appropriate crop rotations, proper application rates for inorganic fertilizers and organic manures, conservation tillage methods, and integrated soil fertility management (Bhattacharyya et al., 2011; Srinivasarao et al., 2012; Wright and Hons, 2005). Such enrichment of the SOC stock will help in maintaining good soil health for sustainable crop production as well as in managing global climate change (Majumder et al., 2008; Mandal et al., 2008).

The dynamics of the SOC pool depends on the balance between carbon (C) input and output through different pathways and is strongly influenced by soil management practices (Ding et al., 2012). A number of studies showed that balanced fertilization with nitrogen (N), phosphorus (P), and potassium (K) in combination with manures increased SOC concentrations and maintained high crop yields (Cai and Qin, 2006; Marriott and Wander, 2006; Purakayastha et al., 2008). After a meta-analysis of published data from 74 studies, Gattinger et al. (2012) concluded that SOC contents in the topsoil layer were 0.18% higher, SOC stocks were 3.5 Mg C ha^{-1} higher, and SOC sequestration rates

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were 0.45 Mg C ha^{-1} yr^{-1} higher in organically farmed soils than in non-organically managed soils. Triberti et al. (2008) reported that manure application could efficiently increase SOC content and that cattle manure had a higher SOC sequestration rate (0.26 Mg C ha^{-1} yr^{-1}) than did slurry (0.18 Mg C ha^{-1} yr^{-1}) and crop residues (0.16 Mg C ha^{-1} yr^{-1}) during a 28-year maize–wheat rotation in Italy southeastern Po Valley. In contrast, other researchers found that the application of inorganic fertilizers destroyed soil structure and caused the loss of organic C (Mikha and Rice, 2004; Wu et al., 2004). However, Cai and Qin (2006) found that the application of N–P–K, N–P, and P–K fertilizer combinations over 14 years increased the SOC stock by 3.7, 2.6, and 0.6 Mg C ha^{-1}, respectively. This uncertainty among studies is attributed partly to the specific processes governing C sequestration under management practices, as those processes vary with soil type, climate, and crop rotation (Liang et al., 2012). Therefore, it is important to assess C sequestration for specific climates, soils, and crop systems to draw site-specific conclusions.

The North China Plain, the largest and most important agricultural region in China, accounts for 18.6% of the country farmland and supports a population of 203 million. This region produces more than 75% and 32% of the national wheat and maize, respectively (China Statistics Bureau, 2011). A long-term field experiment was established in an intensively cultivated sandy loam soil in the North China Plain, where a rotation of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) is practiced, to monitor changes in soil fertility under compost and inorganic fertilizer application. Previous studies showed that long-term compost application and fertilization significantly increased SOC concentrations (Ding et al., 2007) and SOC stocks (Cai and Qin, 2006) in the 0–20 cm soil. However, limited information is available on SOC sequestration in soil profiles as affected by crop management and fertilization. The objectives of the present study were (i) to assess the effect of 20-year of compost and inorganic fertilizer application on the dynamics of the SOC stock in the 0–60 cm soil profile, (ii) to evaluate the influence of compost and inorganic fertilizer on the SOC saturation level and sequestration potential, and (iii) to understand the relationship between SOC sequestration and organic C inputs.

2. Materials and methods

2.1. Site description

A long-term field experiment was established in September 1989 on a well-drained field at the Fengqiu State Key Agro-Ecological Experimental Station, in Fengqiu County, Henan Province, China (35°00′ N, 114°24′ E). Two crops per year, winter wheat (*T. aestivum* L.) and summer maize (*Z. mays* L.), were cultivated. The 30-year mean annual temperature was 13.9 °C, with the lowest mean monthly value, −1.0 °C, in January and the highest mean monthly value, 27.2 °C, in July. The mean precipitation was 615 mm. The soil, derived from alluvial sediments of the Yellow River, is classified as an Aquic Inceptisol and contained 52% sand, 33% silt, and 15% clay. Before the experiment started in 1989, the pre-soil contained 4.48 g kg^{-1} organic C, 0.43 g kg^{-1} total N, 0.50 g kg^{-1} total P, 18.6 g kg^{-1} total K, 1.93 mg kg^{-1} available P, and 78.8 mg kg^{-1} available K.

2.2. Experimental design

The field experiment included seven treatments: compost (CM); half compost N plus half fertilizer N (HCM); fertilizers N, P, and K (NPK); fertilizers N and P (NP); fertilizers N and K (NK); fertilizers P and K (PK); and control without fertilization (CK). The treatments were arranged in a randomized block design with four replicates. Each plot measured 9.5 m by 5 m. The detailed experimental design and the application amounts for the inorganic fertilizers and compost are summarized in Table 1. The basal fertilizers (all the compost and part of the inorganic fertilizers) were broadcast evenly onto the plowed soil (0–20 cm in depth) by tillage before sowing. The supplementary fertilizer urea was surface-applied by hand and then incorporated into the plowed layer with irrigation water or precipitation. For the experiments, the compost was prepared by mixing wheat straw, rapeseed cake, and cottonseed cake in a ratio of 100:40:45 and fermenting the mixture for two months at the experimental farm. This proportion was calculated on the basis of the component C and N contents, with the goal of applying a total amount of organic C in compost (per hectare per season) equal to the amount in harvested wheat straw and an amount of organic N equivalent to 150 kg N ha^{-1}. The wheat straw, rapeseed cake, and cottonseed cake were machine-ground to about 5 mm in length before composting. The rapeseed and cottonseed cakes were machine-dried residues from the extraction of oil from rapeseed and cottonseed and were obtained from a commercial cooking oil business. The amounts of P and K were generally lower than the prescribed doses, so the compost was supplemented with calcium superphosphate and potassium sulfate prior to application. The compost contained 422 g C kg^{-1}, 54.4 g N kg^{-1}, 8.1 g P kg^{-1} and 19.5 g K kg^{-1}.

Maize was sown directly into each plot in early June, and the distances between rows and between hills were 70 and 25 cm, respectively. After two weeks, the seedlings were thinned to about 50,000 per hectare, and the mature maize was harvested in late September. Wheat was sown directly in early October (distance of 15 cm) and

Table 1
Application rates for nitrogen (N), phosphorus (P), potassium (K), and compost for the different treatments as well as average grain yields and amounts of shoot biomass from 1989 to 2009.

Crop	Treatment[a]	Inorganic fertilizer					
		N (kg N ha^{-1})	P (kg P ha^{-1})	K (kg K ha^{-1})	Compost (kg ha^{-1})	Grain yield (kg ha^{-1})	Shoot biomass (kg ha^{-1})
Wheat	CK	0	0	0	0	545.3 d[b]	794.1 c
	NP	150	32.7	0	0	4443.1 a	4747.2 a
	NK	150	0	124.5	0	567.9 d	860.7 c
	PK	0	32.7	124.5	0	1088.8 c	1368.0 c
	NPK	150	32.7	124.5	0	4681.5 a	5169.5 a
	HCM	75	21.5	97.6	1379	4608.7 a	5060.3 a
	CM	0	10.4	70.7	2758	3627.6 b	4090.1 b
Maize	CK	0	0	0	0	821.0 b	2501.5 c
	NP	150	26.2	0	0	6688.8 a	6511.9 a
	NK	150	0	124.5	0	909.2 b	2577.9 c
	PK	0	26.2	124.5	0	1595.2 b	3425.3 b
	NPK	150	26.2	124.5	0	7161.2 a	7070.7 a
	HCM	75	15	97.6	1379	7049.2 a	6846.4 a
	CM	0	3.9	70.7	2758	6365.5 a	6672.8 a

[a] CK, control without fertilization; NP, fertilizer N and P; NK, fertilizer N and K; PK, fertilizer P and K; NPK, fertilizer N, P, and K; HCM, half compost N plus half fertilizer N; and CM, compost.
[b] Values in the same column followed by different lowercase letters are significantly different among treatments at $P < 0.05$.