Soil organic carbon and nitrogen storage under a wheat (*Triticum aestivum* L.)—maize (*Zea mays* L.) cropping system in northern China was modified by nitrogen application rates

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ABSTRACT

Field cultivation practices have changing the carbon and nitrogen cycles in farmland ecosystem, soil organic carbon (SOC) and total nitrogen (TN) were the important parameters in maintaining soil quality and increasing agricultural productivity, however, N application's effects on the SOC and TN storage capacity under intensive wheat-maize cropping system remain unclear. Therefore, we investigated the characteristics and relationships of SOC and TN for wheat-maize cropping system under nitrogen treatments. In doing so, continuous applications of four nitrogen application rates were examined: 0, 180, 240 and 300 kg ha^{-1} (N0, N180, N240 and N300, respectively). Wheat yields under N180 and N240 were significantly higher than that under N300, while the maize yields under N180, N240 and N300 were significantly higher than that under N0 by 79.79, 85.23 and 86.85%, respectively; the TN content and storage were significantly higher under N240 than that under other N levels in 40–60 cm soil layer after wheat growing season; the SOC content and storage under N180 and N240 were significant higher than that under N300 in 20–40 cm after maize growing season. The correlations between SOC and TN contents (or storage) were stronger after wheat planting than maize planting. These findings provide a basis for further studies on the effect of long-term N application on SOC and TN storage, crop quality and nitrogen use efficiency under wheat-maize cropping systems.

INTRODUCTION

Soil organic carbon (SOC) is the most important component of the global carbon (C) cycle (*Shah et al., 2021*), while soil nitrogen (N) dynamics have considerable effects on the terrestrial carbon cycle. In this regard, conservation and storage of SOC in arable soil is becoming increasingly important because of the beneficial effects on soil fertility and subsequent improvements in crop yield, not to mention the mitigating effects on

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climate change (*Baveye et al., 2018*; *UNEP, 2017*). In much of China, wheat and maize yield responses reach a plateau at SOC levels of 21.8–46.2 and 22–44.4 Mg ha^{-1}, respectively (*Wang et al., 2020*). Soil and crop management practices have a significant effect on C and N cycles in cultivated land, altering the quantity and quality of crop residues in the soil as well as the overall supply of nutrients (*Dou et al., 2018*; *McDaniel et al., 2014*; *Tian et al., 2015*). In agricultural ecosystems, fertilizer management is an important factor that affects SOC sequestration, crop production and food security (*Ren et al., 2021*).

The N dynamics affects C sinks through the processes of biological, physical and chemical about fine root turnover, litter decomposition, soil respiration and photosynthetic characteristics (*Mandal et al., 2022*). Terrestrial C–N interactions are extremely important in determining the long-term sustainability of C sinks in land ecosystems (*Deng et al., 2016*). The N dynamics are thought to be an important determining factor in terms of long-term C sequestration in agroecosystems, influencing the concentration of plant available nutrients, promoting the crop growth of aboveground and belowground, and affecting the biodegradation of soil organic matter (*Li et al., 2015*; *Meng et al., 2016*). In China, a series of long-term experiments was carried out during the 1980s and early 1990s to examine the effects of nutrient management on soil fertility, crop productivity, and nutrient use efficiency (*Duan et al., 2014*; *Yang, Sun & Zhang, 2014*). However, few integrated studies have examined the yield and SOC dynamics in deep soil under long-term winter wheat-summer maize cropping systems. Understanding how N enrichment affects cropland C cycling is essential in understanding the effect of increasing N input on global climatic change.

Chemical fertilizer can provide nutrients supply for crop growth, and have becoming a common agricultural management practice for improving the crop yield (*Duan et al., 2011*; *Zhang et al., 2016*). In China's croplands, excessive use of synthetic chemical fertilizers have led to a decrease in soil quality, resulting in a number of adverse agricultural impacts (*Liu & Diamond, 2005*). Various studies have examined C sequestration and the possibility of mitigating SOC losses by optimizing crop rotation, application rates of inorganic fertilizers and the integration of soil fertility management (*Berhane et al., 2020*; *Srinivasarao et al., 2012*). Development of appropriate management practices aimed at sustainable crop productivity and increased SOC sequestration on a regional and global scale is therefore crucial in terms of soil fertility and productivity (*FAO, 2011*).

Wheat–maize rotation is the principal cropping system in the North China Plain, covering approximately 16 M ha and accounting for about 25% of the total national food production (*Yang, Sun & Zhang, 2014*). In the past two decades, excessive synthetic chemical fertilizer application during winter wheat-summer maize production, especially in the form of N, has been increased from 7.07 to 26.21 million tons (*Guan et al., 2020*), influencing the sustainability of future cereal production dramatically (*Bei et al., 2018*; *Chen et al., 2014*). Previous studies have examined the changes in SOC levels based on single fertilizer management (*Ji et al., 2016*), specific crops (*Tian et al., 2015*), and under single-cropping systems and specific soil types (*Zha et al., 2015*). However, the long-term effects of different N application levels on SOC and N storage under wheat–maize cropping system need to be quantified in greater detail. The aims of this study, therefore, were to (1)

determine the effects of different N application rates on SOC and TN concentrations; (2) compare the C content of wheat and maize biomass during crop rotation; and (3) analyze SOC and N storage and the correlations between SOC and TN with depth.

MATERIALS AND METHODS

Experimental site and climatic conditions

This long-term study was established in July 2012 at Zhangpan Town, Jian'an District, Xuchang City, Henan Province (33°59′N, 113°58′E), China, and field management practices were treated in the same way. Observations for this study were made during the 2017–2018 growing season. The area has a temperate monsoon climate, with annual mean precipitation and temperature of 712 mm and 14.6 °C, respectively. About 60% of the precipitation falls between the months of July and September. The predominant cropping system is double-cropping rotation of winter wheat and summer maize.

The soil type is mortar black soil, with 13.04 and 10.43 g kg^{-1} organic matter, 0.72 and 0.85 g kg^{-1} total N, 0.79 and 0.84 g kg^{-1} total phosphorus, 6.58 and 6.99 g kg^{-1} total potassium, and bulk density were 1.39 and 1.47 g cm^{-3} for wheat and maize in the 0–20 cm soil profile, respectively. Agricultural production levels and the natural conditions of the experimental site are representative of high-yielding winter wheat production in this region.

Experimental design and field management

The high-yielding wheat and maize cultivars of Aikang 58 and Denghai 678 respectively were used in this study, representing the most commonly planted wheat and maize cultivar in Huanghuai area, wheat and maize were sown in sequence in the same plot. The field experiment consisted of three replicates for each N treatment applied in a randomized block design with four N application rates of 0, 180, 240, and 300 kg ha^{-1} (N0, N180, N240, and N300, respectively). Each plot was 10 × 11 m, with a seeding rate of 187.5 and 30 kg ha^{-1} for wheat and maize, respectively. At the time of sowing, chemical fertilizer comprising 60% urea and 40% sulfur-coated urea was applied by hand before plowing at a rate of 66 kg P ha^{-1} and 72 kg K ha^{-1}. Prior to sowing, plowing was carried out to remove pests and weeds, and during the growing period, weeds were hand-hoed several times.

Soil samples and preparation

After the wheat and maize were harvested, the root system was excavated with shovel to a size of 20 cm (length) × 20 cm (width) × 40 cm (depth) then washed with deionized water, and the above-ground parts were sampled with scissor or axe from the root. Soil samples were collected from the soil layers (every 20 cm up to a depth of 60 cm) in all 12 subplots on May 28 and September 28, 2018 subsequently. Three soil cores (inner diameter: 5.0 cm) were randomly sampled from each subplot then mixed to form one fresh sample for each depth increment. Visible plant material was removed then soil samples were divided into three parts and transported to the laboratory, where they were air dried before passing through a two mm screen. Roots and other debris were then removed before further analysis. The bulk density (BD) of the soil was measured in different layers using a soil

bulk sampler with a stainless steel cutting ring (inner diameter: 5.0 cm, height: 5.0 cm) at points adjacent to the soil sampling plots. First, the volume of each soil core was measured then the dry mass was determined after oven drying at 105 °C.

Analysis of soil physical and chemical properties

The dichromate oxidation method was used to measure the SOC and the Kjeldahl method (Kjeltec 2300 Analyzer Unit; Foss, Hogana, Sweden) was used to analyze the TN (*Bremner, 1996*; *Nelson & Sommers, 1982*). Soil pH was measured using a pH meter after shaking for 30 min with a soil: water suspension of 1: 2.5 w/v. Each measurement was performed in triplicate.

Analysis of soil C and N stocks and soil C and N sequestration

Since no coarse fraction (>2 mm) was found in the soil samples, the following equation was used to calculate the soil C stock (C_s, Mg ha^{-1}):

$$C_s = (SOC \times BD \times D)/10 \qquad (1)$$

where BD is the soil bulk density (g cm^{-3}), SOC is the soil organic carbon concentration (g kg^{-1}) and D is the depth of the sampled soil layer (cm). The following equation was used to calculate the soil N stock (N_s, Mg ha^{-1}):

$$N_s = (TN \times BD \times D)/10 \qquad (2)$$

where BD and D are as above and TN is the total N concentration (g kg^{-1}) of the soil.

The C_s and N_s values were then used to determine C and N sequestration (ΔC_s and ΔN_s, Mg ha^{-1}) after maize planting as follows:

$$\Delta C_s = C_m - C_w \qquad (3)$$
$$\Delta N_s = N_m - N_w \qquad (4)$$

where C_m is the soil C stock after maize planting (Mg ha^{-1}), C_w is the C stock after wheat planting (Mg ha^{-1}), N_m is the soil N stock after maize planting (Mg ha^{-1}) and N_w is the N stock at maize planting (Mg ha^{-1}).

Statistical analyses

Data were analyzed using SPSS software version 17.0 (IBM Corp., Armonk, NY, USA). Duncan's multiple range test was used for variance analysis and to compare mean values ($n = 3$) at a significance level of 0.05.

RESULTS

Crop yield

For wheat field, the grain yields under N180, N240 and N300 were significantly higher than that under N0 by 184.67, 191.11 and 173.24%, respectively; the yields under N180 and N240 were significantly higher than that under N300 ($P < 0.05$). For maize field, the grain yields under N180, N240 and N300 were significantly higher than that under N0 by 79.79, 85.23 and 86.85%, respectively ($P < 0.05$); there were no significant differences among N180, N240 and N300 (Fig. 1).
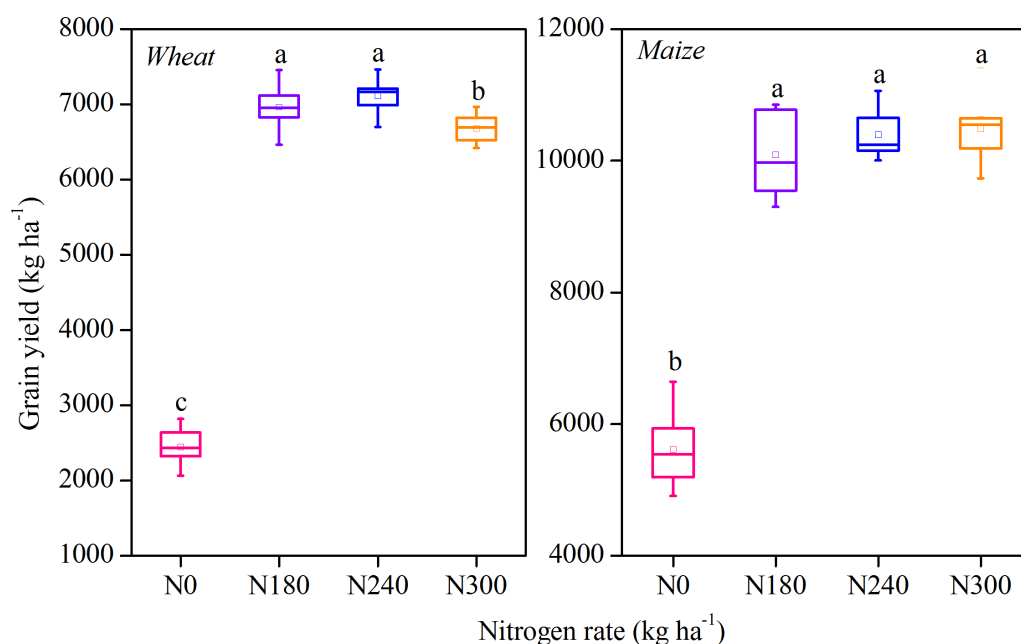
Figure 1 Annual mean grain yield in winter wheat (left panel) and summer maize (right panel) after long-term application of different nitrogen rates (N0, N180, N240 and N300). The box represents ± SE, the whisker represents the Min-Max, the small square represents the mean values, and the horizontal line is the median.

The SOC and TN content

In wheat growing season, SOC and TN were highest in 0–20 cm soil layer, with no significant differences among N levels, the TN was significantly lower under N240 than that under other N levels in 20–40 cm layer, but was significantly higher in 40–60 cm layer ($P < 0.05$) (Fig. 2). In maize growing season, SOC and TN were also highest in 0–20 cm, the SOC under N180, N240 and N300 were significant higher than that under N0 in 0–20 cm layer, the values under N180 and N240 were significant higher than N300 in 20-40 and 40–60 cm ($P < 0.05$). In the entire profile, SOC values were higher after wheat planting than maize planting, while TN were higher under N240 and N300 after maize planting than that after wheat planting.

The SOC and N storage

In wheat growing season, SOC and TN storage were highest in the 0–20 cm soil layer, the SOC and TN storage were significant lower than that under other N treatments in 20–40 cm under N240, and the TN storage were significant higher in 40–60 cm under N180 and N240 ($P < 0.05$) (Figs. 3A and 3B). The SOC and TN storage was highest in the entire profile under N180. In maize growing season, the SOC storage was significant higher in 0–20 cm layer under N300, but that under N0, N180 and N240 were significant higher than that under N300 in 20–40 cm ($P < 0.05$) (Fig. 3), the SOC storage was highest in the entire profile under N180, with lowest values under N300. In contrast, TN storage was higher under N240 and N300. The SOC storage in the entire profile was higher after wheat
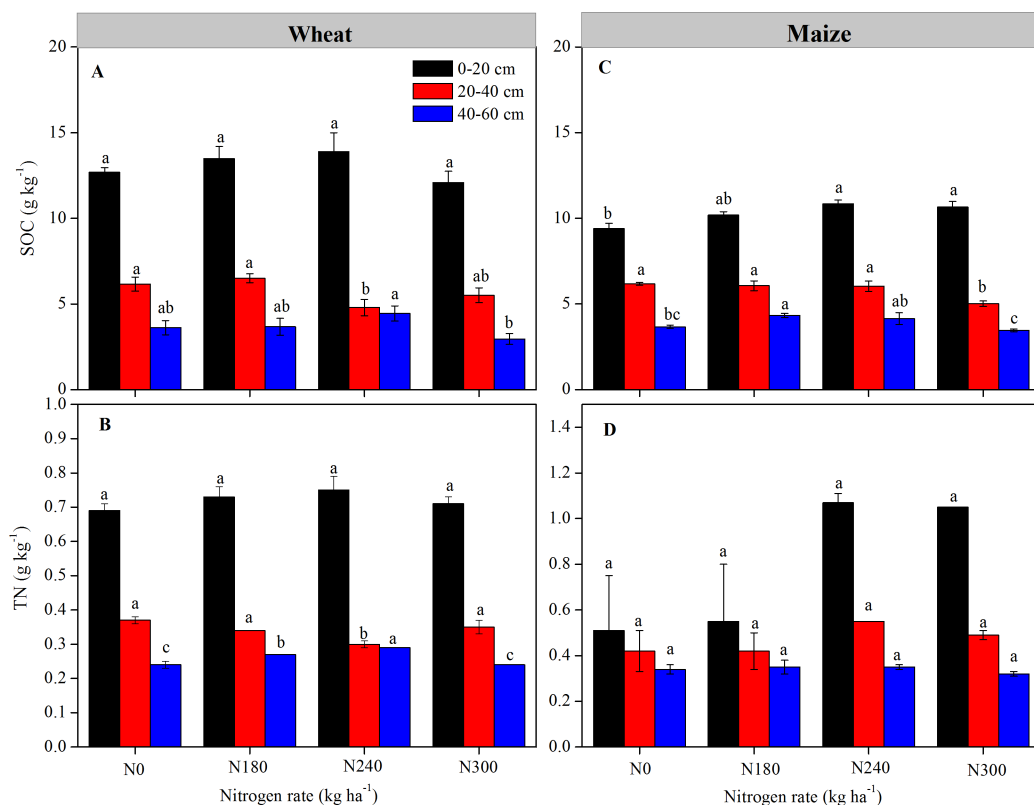
Figure 2 (A & C) Soil organic carbon (SOC) and (B & D) total nitrogen (TN) levels in each soil layer under each nitrogen application rates. Values represent means ± SE. Different lowercase letters above the bars represent significant differences in the same soil layer between different nitrogen levels ($P < 0.05$).

planting than maize planting under all N levels, while TN storage was higher after maize planting, especially under N240 and N300 treatment.

Relationships between SOC and TN content, and SOC and TN storage after wheat and maize planting

The SOC and TN content plus SOC and TN storage were significantly positively correlated, respectively ($P < 0.01$, Fig. 4). Correlations between soil SOC and TN, and soil C and N storage were also stronger after wheat planting than maize planting. Moreover, the correlations between SOC and TN storage were greater than those between SOC and TN content in wheat and maize growing seasons.

The biomass, SOC content and storage of above and belowground organs

The biomass of wheat and maize were significant increased after adding N, but the SOC content and storage have no significant difference among N treatments for wheat. For maize, the SOC storage of above and belowground were significant higher under N180 and
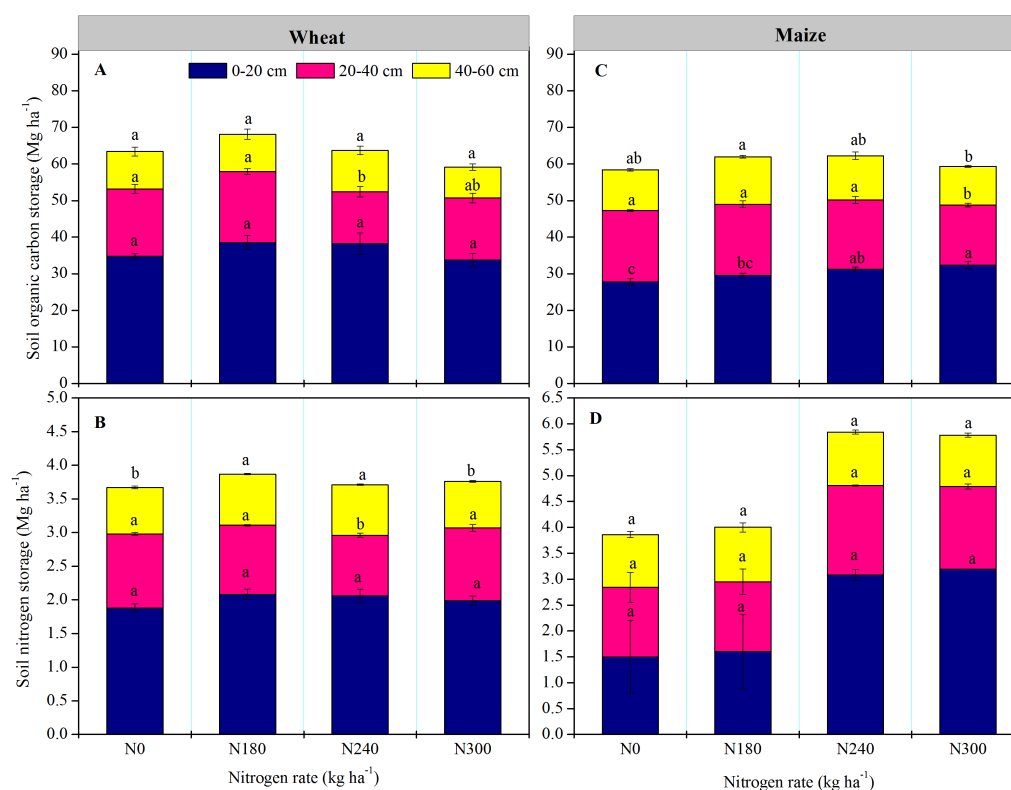
Figure 3 (A & C) Soil organic carbon (SOC) and (B & D) total nitrogen (TN) storage in each soil layer under each nitrogen application rate. Values represent means ± SE. Different lowercase letters above the bars represent significant differences in the same soil layer between different nitrogen levels ($P < 0.05$).

N240 than that under N0 treatment, and the SOC content was highest under N240 than that under other N treatments (Table 1).

Differences in SOC and TN sequestration after maize planting

The SOC and TN sequestration were different in soil depths and N levels (Fig. 5). The SOC sequestration in the 0–20 cm soil layer decreased following maize harvest , while in the subsoil layers (>20 cm), SOC and TN sequestration increased under almost all N levels. The SOC sequestration was highest in the 20–40 cm layer under N240 (4.81 Mg ha^{-1}), followed by the 40–60 cm under N180 treatment. In the 20-40 and 0–60 cm soil layer, TN sequestration was highest at N240 level. The higher TN sequestration were observed under N240 and N300 compared to N0 and N180 across 0-60 soil profile.

Correlations between SOC, TN storage and soil properties

The SOC (or TN) storage and SOC (or TN) content were significantly positively correlated at each soil depth in both wheat and maize; in wheat, SOC storage and C/N were significantly positively correlated across the entire soil profile. No significant correlations were observed between SOC storage and BD in maize or between N storage and SOC content in both wheat and maize (Table 2).
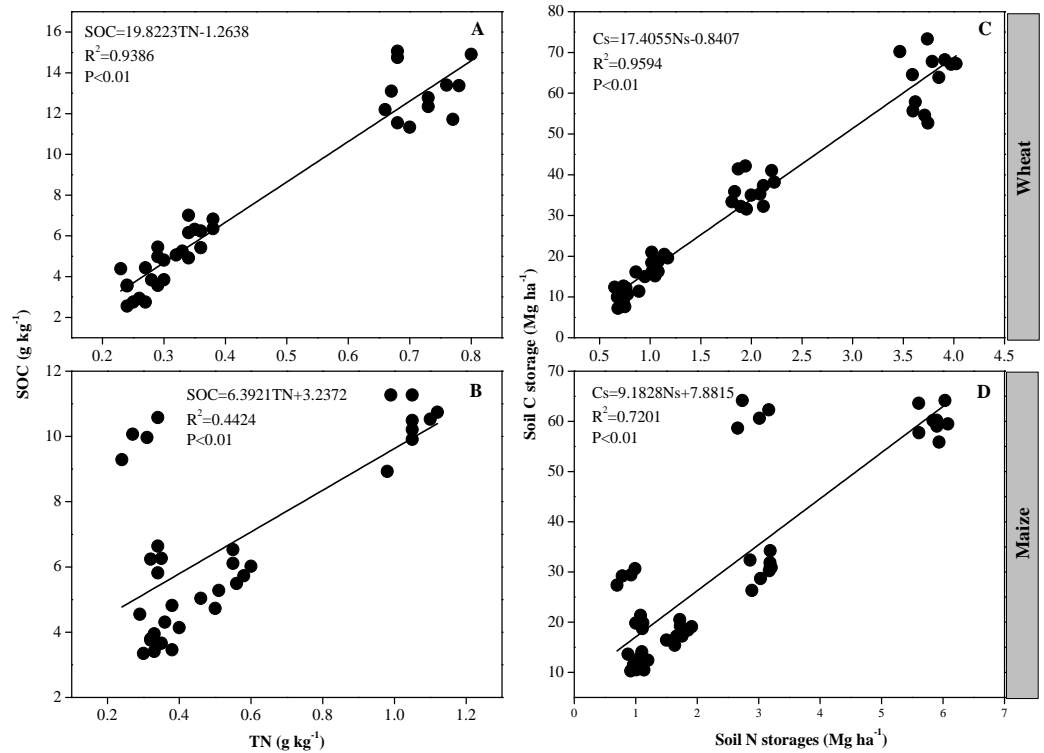
Figure 4 (A–D) Correlations between soil organic carbon (SOC) and total nitrogen (TN) contents, and SOC and TN storage.

DISCUSSION

Effect of N fertilizer on crop yield

The findings of this study revealed that annual N application increased crop yield compared with control treatment (N0) during the study period. Mean wheat yield was in the order of N240 > N180 > N300 > N0, with significantly higher yield under N180 and N240, similar to a previous report (*Wang et al., 2018*). In contrast, maize yield was highest under N300 treatment, and was in the order of N300 > N240 > N180 > N0, suggesting that maize has a higher demand for N fertilizer. It was previously revealed that fertilizer treatment significantly increased crop production compared to no fertilizer application (*Chen et al., 2015*), although the yields under different fertilizer treatments were not significant in both wheat and maize, thus differing from our results. This difference was attributed to the larger amount of crop stubble returned to the soil in the fertilized plots as a result of the increase in crop yield. In other words, a larger grain yield, especially in terms of straw and stalk biomass, inevitably leads to an increase in residue return to the soil compared to no fertilizer or synthetic fertilizer treatment (*Huang et al., 2010*; *Xie et al., 2017*), thereby increasing C sequestration.

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Table 1 The biomass, carbon content and storage of above and belowground organs of wheat and maize under nitrogen treatments.

Component	N0			N180			N240			N300		
	Biomass (Mg ha^{-1})	Carbon content (g kg^{-1})	Carbon storage (Mg ha^{-1})	Biomass (Mg ha^{-1})	Carbon content (g kg^{-1})	Carbon storage (Mg ha^{-1})	Biomass (Mg ha^{-1})	Carbon content (g kg^{-1})	Carbon storage (Mg ha^{-1})	Biomass (Mg ha^{-1})	Carbon content (g kg^{-1})	Carbon storage (Mg ha^{-1})
Wheat												
Aboveground	2.69[b]	402.33[a]	1.83[a]	7.75[a]	421.93[a]	2.59[a]	7.31[a]	455.5[a]	2.78[a]	7.11[a]	419.2[a]	3.16[a]
Belowground	0.22[b]	427.5[a]	0.32[a]	0.79[a]	378.6[a]	0.21[a]	1.04[a]	337.47[a]	0.21[a]	0.97[a]	382.80[a]	0.39[a]
Total	2.90[b]	–	2.16[a]	8.53[a]	–	2.80[a]	8.34[a]	–	2.99[a]	8.08[a]	–	3.55[a]
Maize												
Aboveground	4.67[b]	359.49[a]	1.68[b]	6.58[a]	397.75[a]	2.63[a]	7.29[a]	388.46[a]	2.84[a]	7.66[a]	426.32[a]	3.26[a]
Belowground	1.17[b]	323.34[b]	0.38[b]	1.90[a]	347.75[ab]	0.66[a]	1.83[a]	378.85[a]	0.69[a]	1.65[a]	263.48[c]	0.43[b]
Total	5.84[b]	–	2.06[b]	8.48[a]	–	3.29[a]	9.12[a]	–	3.53[a]	9.30[a]	–	3.69[a]

Notes.

Different lowercase letters represent significant differences among nitrogen treatments ($P < 0.05$). Aboveground parts exclude the panicle grain.
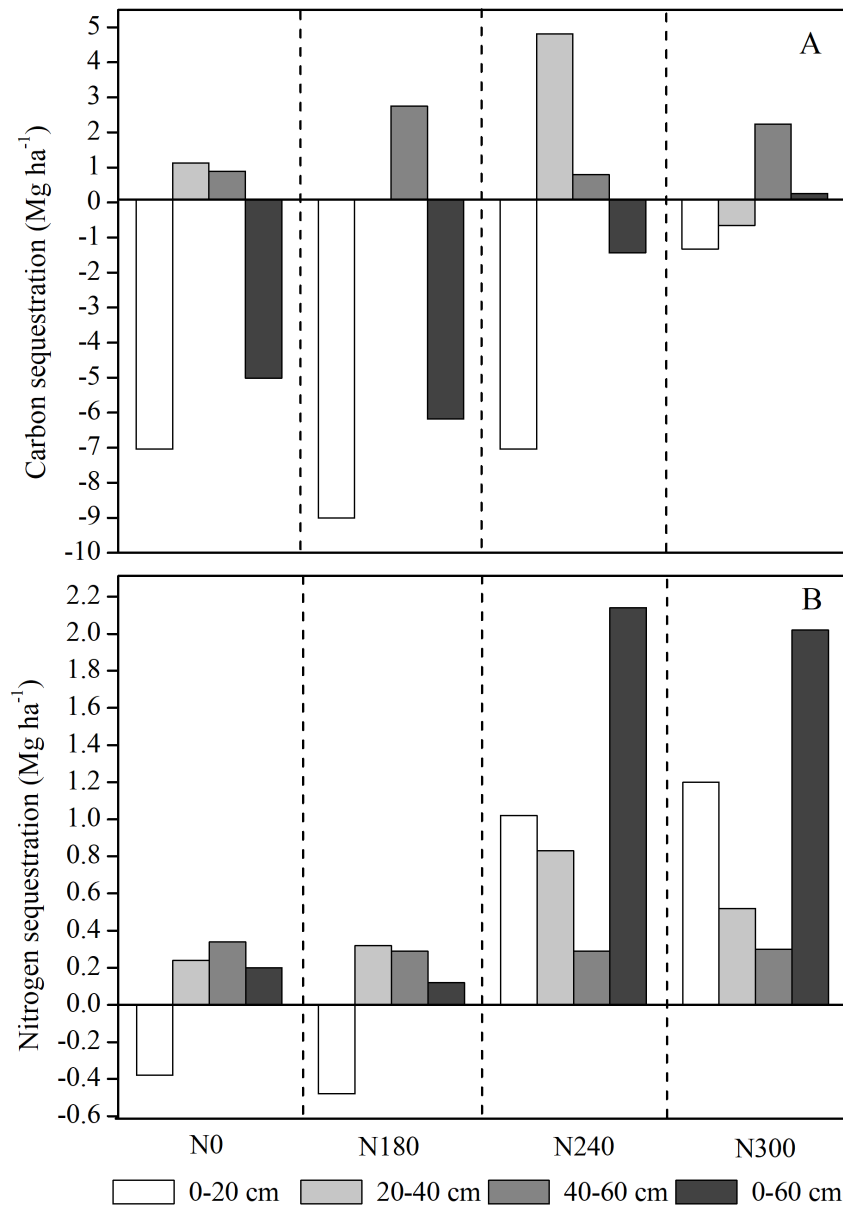
Figure 5 (A) Carbon and (B) nitrogen sequestration in each soil layer under each nitrogen level after maize planting.

Content and storage of SOC and N

Soil organic C affects soil functions and processes, thereby affecting nutrient availability for plants (*Troeh & Thompson, 2005*). Fertilization effects on SOC show regional differences, and in our study, SOC and TN content decreased gradually with increasing soil depth under all N treatments, with highest contents in the 0–20 cm layer. This is thought to be because the rate of decay of soil C is faster in deeper soil layers, consistent with previous findings in northeast China and the Loess Plateau (*Wang et al., 2011a*; *Wang, Wang & Zu, 2014*).

Table 2 Pearsons's correlation coefficients between soil C and N storage and soil properties (C/N: carbon/nitrogen and BD: bulk density) at each soil depth.

Crop		Soil properties							
Wheat	Soil layer	Soil carbon storage				Soil nitrogen storage			
		SOC	TN	C/N	BD	SOC	TN	C/N	BD
	0–20 cm	0.984**	0.316	0.730*	−0.364	0.402	1.000**	−0.105	−0.252
	20–40 cm	0.658*	0.699*	0.324	0.320	0.082	1.000**	−0.321	0.167
	40–60 cm	0.767**	0.296	0.794**	−0.514	0.463	1.000**	0.252	−0.584*
	0–60 cm	0.984**	0.242	0.901**	−0.127	0.216	1.000**	−0.186	−0.340
Maize	0–20 cm	0.947**	0.391	−0.360	0.163	0.356	0.998**	−0.988**	0.262
	20–40 cm	0.993**	−0.363	0.671*	−0.046	−0.354	0.997**	−0.944**	−0.242
	40–60 cm	0.991**	0.184	0.742**	−0.157	0.097	0.982**	−0.601*	−0.092
	0–60 cm	0.957**	−0.218	0.336	0.200	−0.213	0.998**	−0.992**	−0.100

Notes.
*Significant correlations at $P = 0.05$ ($P < 0.05$) (2-tailed) in a sample size of $n = 12$.
**Significant correlations at $P < 0.01$ (2-tailed) in a sample size of $n = 12$.

In northern China, soil organic C and N conditions in both upper and deeper soil layers are significantly affected by N levels, and in this study, TN values were higher under N240 and N300 treatment during the maize compared to wheat season. This is probably why maize yield increased with increasing N fertilizer application. Moreover, SOC values were higher during the wheat compared to maize season in the entire profile. This is thought to be because increased rainfall during the maize season have resulted in a relatively higher soil moisture content, resulting in a more favorable soil environment for rapid propagation of soil microorganisms, and subsequent acceleration of SOC mineralization and decomposition (*Silver & Miya, 2001*; *Wang et al., 2020*; *Zhang et al., 2010*). In contrast, during the winter wheat growth period, rainfall was lower, and activity of microorganisms in the soil was likely to be lower, thereby slowing the rate of SOC decomposition. Moreover, wheat stubble returned to the maize field has a higher ratio of C: N than maize stubble, which is also likely to have had an effect on SOC decomposition (*Zhao et al., 2016*).

Cropping systems have a significant effect on SOC stocks, influencing the balance between C input from litter and C losses *via* decomposition (*Huang, Sun & Zhang, 2012*). In general, soil depth is stable, suggesting that soil C stocks are determined by SOC and soil BD (*Deng et al., 2013*). In this study, soil SOC and TN storage was highest in the 0–20 cm layer under all N levels in both wheat and maize. Nutrient and organic matter accumulation in the topsoil is the result of complex interactions between biotic processes regulated by plants and soil biota, and abiotic processes driven by environmental processes (*Hooper, Bignell & Brown, 2000*). Land use and the depth of sampling are therefore important in terms of SOC and soil C measurements (*Strahm et al., 2009*; *VandenBygaart et al., 2010*). In this study, SOC and TN storage were high under N180 for wheat and SOC storage showed no further increases with increasing N application. Soil nutrients are gradually depleted during continuous cropping under no fertilizer application, thereby affecting SOC dynamics and stability (*Zhang et al., 2010*). Thus, overall, balanced chemical fertilizer use combined with straw application is the most beneficial to SOC stocks.

Correlations between SOC and TN content, SOC and TN storage after wheat and maize planting

After wheat and maize planting, soil SOC and TN, and soil C and N storage were significantly positive correlated ($P < 0.01$). *Deng et al. (2018)* also observed a significant positive correlation between soil C and N on the Loess Plateau in vegetation succession, while a significant positive effect of N enrichment on SOC was also revealed in globally syntheses (*Liu & Greaver, 2010*; *Lu et al., 2011*). The correlations of soil C and N storage were different between wheat and maize planting, probably because SOC stocks are affected by a number of soil chemical and physical properties (*Wang et al., 2013*), and they differed following long-term N treatments in this study.

The biomass, SOC content and storage of aboveground and belowground organs

Different crop types result in different litter decomposition processes, thereby affecting the release of C and N into the soil (*Zhang et al., 2013*). Aboveground vegetation plays an essential role in regulating the biogeochemistry of different ecosystems, fixing C and nutrients and preventing nutrient losses following disturbance. In this study, the above and belowground biomass of both wheat and maize were significantly higher following N application compared to N0 treatment. It is well known that N fertilization has a positive effect on plant growth, with aboveground net primary productivity and belowground biomass both increasing in response to increasing N application (*Peng, Guo & Yang, 2017*; *Tang et al., 2017*).

In this study, the SOC content and storage of above and belowground wheat organs did not significantly differ between N treatments, similar to a previous report showing that the level of N application had no effect on SOC, with N addition increasing aboveground plant productivity but not root input into the soil C pool (*King et al., 2005*). Meanwhile, in maize, no significant differences in aboveground SOC was observed between N treatments, although belowground SOC content and storage was significantly higher under N180 and N240. A significant increase in C stocks with N application was previously observed in both above and belowground biomass, suggesting that N treatment stimulates biomass accumulation, thereby increasing C and nutrient retention in the soil (*Lu et al., 2011*). Overall, these findings suggest that results differ between crop types.

Differences between SOC and TN sequestration under different N levels after maize planting

The N levels and soil layers had a significant effect on SOC and N sequestration. The primary productivity of litter and roots have a significant effect on soil carbon sequestration, resulting primarily in an accumulation of SOC and N storage in the topsoil layer (*Cheng et al., 2006*; *Dou et al., 2018*). In this study, soil SOC sequestration in the 0–20 cm soil layer decreased under all N treatments, while both SOC and TN sequestration almost tended to increase in the 20–60 cm layer after maize planting for all N treatments. This is thought to be because larger maize roots are distributed at a depth of 20–30 cm (*Dou et al., 2016*), while soil C and N in the topsoil layer are lost rapidly, possibly due to soil respiration and incomplete decomposition soil organic matter in residues (*Cheng et al., 2006*). The N
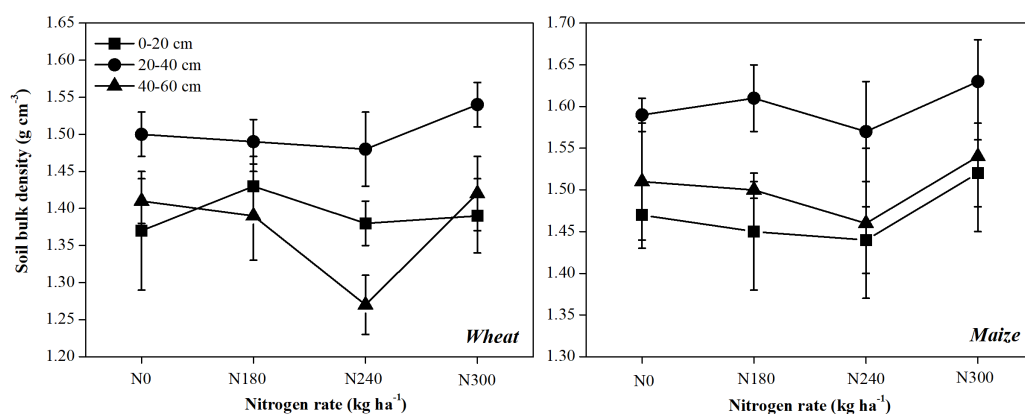
Figure 6 Dynamics of soil bulk density in at each soil depth under each nitrogen application rate.

dynamics are another key factor affecting long-term terrestrial C sequestration (*Luo, Field & Jackson, 2006*). In this study, SOC and TN sequestration were at their highest in the 20–40 cm layer at N240 under all the treatments. The SOC sequestration almost tended to decrease in the 0–60 cm soil profile under N treatments; however, N sequestration were all increased, and was significantly higher under N240 and N300 treatment. These findings suggest that the consumption of SOC is greater than production, with combined application of N fertilizer and straw working together to increase N sequestration during the maize growing season. In addition, soil particle size, and the composition and dynamics of microbial communities as well as the increase in biomass with increasing N levels also have an effect on the biogeochemical cycles of soil carbon and N (*Cleveland et al., 2004*; *Li et al., 2005*), thereby increasing rates of carbon sequestration.

Pearson's correlation coefficients between SOC, TN storage and soil properties

In this study, SOC and TN storage and contents of SOC and TN were significantly positively correlated in each soil layer after both wheat and maize planting, suggesting that SOC and TN storage are the result of soil C and N accumulation. Meanwhile, there were respective negative correlations between SOC and TN storage and BD, except in the 20–40 cm layer after wheat planting and the 0–20 cm layer after maize planting (Table 2). *Wang et al. (2011b)* revealed a negative relationship between SOC and TN with soil bulk density, while *Singh et al. (2012)* and *Singh, Singh & Singh (2012)* reported a significant increase in SOC and TN but a significant decrease in BD during the restoration of degraded land. In this study, BD differed between soil layers (Fig. 6), suggesting that the differences between studies were due to differences in soil characteristics and/or the crop type.

CONCLUSIONS

This study investigated the SOC and TN characteristics of wheat-maize cropping system under different N application rates. The findings of this study suggest that long-term application of chemical fertilizers could significantly improve yield, especially after N180

and N240 treatments. The SOC and TN decreased gradually with increasing soil depth under four N treatments, SOC values were higher after wheat than that after maize planting. Correlations between SOC and TN content, SOC and N storage were stronger after wheat than that after maize planting. Meanwhile, SOC and TN sequestration were lower under N180 than that under other N treatments after maize planting, suitable N application aiding improvements in crop quality and efficiency.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Lifang Wang conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.
- Shijie Liu performed the experiments, prepared figures and/or tables, and approved the final draft.
- Geng Ma conceived and designed the experiments, prepared figures and/or tables, and approved the final draft.
- Chenyang Wang conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Jutao Sun analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The raw measurements are available in the Supplementary File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.13568#supplemental-information.

REFERENCES

Baveye PC, Berthelin J, Tessier D, Lemaire G. 2018. The 4 per 1000 initiative: a credibility issue for the soil science community? *Geoderma* **309**:118–123 DOI 10.1111/gcb.15018.

Bei S, Zhang Y, Li T, Christie P, Li X, Zhang J. 2018. Response of the soil microbial community to different fertilizer inputs in a wheat-maize rotation on a calcareous soil. *Agriculture Ecosystems & Environment* **260**:58–69 DOI 10.1016/j.agee.2018.03.014.

Berhane M, Xu M, Liang ZY, Shi JL, Wei GH, Tian XH. 2020. Effects of long-term straw return on soil organic carbon storage and sequestration rate in North China upland crops: a meta-analysis. *Global Change Biology* **26**:2686–2701 DOI 10.1111/gcb.15018.

Bremner J. 1996. *Nitrogen-total. Methods of soil analysis. Part 3.* Madison: Soil Science Society of America, 1085–1121.

Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X, Yang J, Deng X, Gao Q, Zhang Q, Guo S, Ren J, Li S, Ye Y, Wang Z, Huang J, Tang Q, Sun Y, Peng X, Zhang J, He M, Zhu Y, Xue J, Wang G, Wu L, An N, Wu L, Ma L, Zhang W, Zhang F. 2014. Producing more grain with lower environmental costs. *Nature* **514**:486–489 DOI 10.1038/nature13609.

Chen H, Zhao Y, Feng H, Li H, Sun B. 2015. Assessment of climate change impacts on soil organic carbon and crop yield based on long-term fertilization applications in Loess Plateau, China. *Plant and Soil* **390**:401–417 DOI 10.1007/s11104-014-2332-1.

Cheng X, Luo Y, Chen J, Lin G, Chen J, Li B. 2006. Short-term C_4 plant Spartina alterniflora invasions change the soil carbon in C_3 plant-dominated tidal wetlands on a growing estuarine island. *Soil Biology & Biochemistry* **38**:3380–3386 DOI 10.1016/j.soilbio.2006.05.016.

Cleveland CC, Townsend AR, Constance BC, Ley RE, Schmidt SK. 2004. Soil microbial dynamics in Costa Rica: seasonal and biogeochemical constraints. *Biotropica* **36**:184–195 DOI 10.1111/j.1744-7429.2004.tb00311.x.

Deng L, Wang KB, Chen ML, Shangguan ZP, Sweeney S. 2013. Soil organic carbon storage capacity positively related to forest succession on the Loess Plateau, China. *Catena* **110**:1–7 DOI 10.1016/j.catena.2013.06.016.

Deng L, Wang GL, Liu GB, Shangguan ZP. 2016. Effects of age and land-use changes on soil carbon and nitrogen sequestrations following cropland abandonment on the Loess Plateau, China. *Ecological Engineering* **90**:105–112 DOI 10.1016/j.ecoleng.2016.01.086.

Deng L, Wang KB, Zhu GY, Liu YL, Chen L, Shangguan ZP. 2018. Changes of soil carbon in five land use stages following 10 years of vegetation succession on the Loess Plateau, China. *Catena* **171**:185–192 DOI 10.1016/j.catena.2018.07.014.

Dou X, He P, Cheng X, Zhou W. 2016. Long-term fertilization alters chemically-separated soil organic carbon pools: based on stable C isotope analyses. *Scientific Reports* **6**:19061 DOI 10.1038/srep19061.

Dou X, Li F, Cheng X, Zhu P. 2018. Soil organic carbon and nitrogen dynamics induced by continuous maize cropping compared to maize–soya bean rotation. *European Journal of Soil Science* **69**:535–544 DOI 10.1111/ejss.12544.

Duan YH, Xu MG, Gao SD, Yang XY, Huang SM, Liu HB, Wang BR. 2014. Nitrogen use efficiency in a wheat-corn cropping system from 15 years of manure and fertilizer applications. *Field Crops Research* **157**:47–56 DOI 10.1016/j.fcr.2013.12.012.

Duan Y, Xu M, Wang B, Yang X, Huang S, Gao S. 2011. Long-term evaluation of manure application on maize yield and nitrogen use efficiency in China. *Soil Science Society of America Journal* **75**:1562–1573 DOI 10.2136/sssaj2010.0315.

FAO. 2011. *The state of the world's land and water resources for food and agriculture (SOLAW)-managing systems at risk.* London: Food and Agriculture Organization of the United Nations, Rome and Earthscan.

Guan XK, Wei L, Turner NC, Ma SC, Yang MD, Wang TC. 2020. Improved straw management practices promote in situ straw decomposition and nutrient release, and increase crop production. *Journal of Cleaner Production* **250**:119514 DOI 10.1016/j.jclepro.2019.119514.

Hooper DU, Bignell DE, Brown VK. 2000. Interactions between aboveground and belowground biodiversity in terrestrial ecosystems: patterns, mechanisms and feedbacks. *Bioscience* **50**:1049–1061 DOI 10.1641/0006-3568(2000)050[1049:IBAABB]2.0.CO;2.

Huang S, Peng X, Huang Q, Zhang W. 2010. Soil aggregation and organic carbon fractions affected by long-term fertilization in a red soil of subtropical China. *Geoderma* **154**:364–369 DOI 10.1016/j.geoderma.2009.11.009.

Huang S, Sun Y, Zhang W. 2012. Changes in soil organic carbon stocks as affected by cropping systems and cropping duration in China's paddy fields: a meta-analysis. *Climatic Change* **112**:847–858 DOI 10.1007/s10584-011-0255-x.

Ji Q, Zhao S, Li Z, Ma Y, Wang X. 2016. Effects of Biochar-straw on soil aggregation, organic carbon distribution, and wheat growth. *Agronomy Journal* **108**:2129–2136 DOI 10.2134/agronj2016.02.0121.

King JS, Kubiske ME, Pregitzer KS, Hendrey GR, McDonald EP, Giardina CP, Quinn VS, Karnosky DF. 2005. Tropospheric O_3 compromises net primary production in young stands of trembling aspen, paper birch and sugar maple in response to elevated atmospheric CO_2. *New Phytologist* **168**:623–635 DOI 10.1111/j.1469-8137.2005.01557.x.

Li WB, Jin CJ, Guan DX, Wang QK, Wang AZ, Yuan FH, Wu JB. 2015. The effects of simulated nitrogen deposition on plant root traits: a meta-analysis. *Soil Biology & Biochemistry* **82**:112–118 DOI 10.1016/j.soilbio.2015.01.001.

Li YY, Shao MA, Zheng JY, Zhang XC. 2005. Spatial–temporal changes of soil organic carbon during vegetation recovery at Ziwuling, China. *Pedosphere* **15**:601–610.

Liu J, Diamond J. 2005. China's environment in a globalizing world. *Nature* **435**:1179–1186 DOI 10.1038/4351179a.

Liu LL, Greaver TL. 2010. A global perspective on belowground carbon dynamics under nitrogen enrichment. *Ecology Letters* **13**:819–828 DOI 10.1111/j.1461-0248.2010.01482.x.

Lu M, Zhou XH, Luo YQ, Yang YH, Fang CM, Chen JK, Li B. 2011. Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis. *Agriculture Ecosystems & Environment* **140**:234–244 DOI 10.1016/j.agee.2010.12.010.

Luo YQ, Field CB, Jackson RB. 2006. Does nitrogen constrain carbon cycling, or does carbon input stimulate nitrogen cycling? *Ecology* **87**:3–4 DOI 10.1890/05-0923.

Mandal A, Majumder A, Dhaliwal SS, Toor AS, Mani PK, Naresh RK, Gupta RK, Mitran T. 2022. Impact of agricultural management practices on soil carbon sequestration and its monitoring through simulation models and remote sensing techniques: a review. *Critical Reviews in Environmental Science and Technology* **52**:1–49 DOI 10.1080/10643389.2020.1811590.

McDaniel MD, Grandy AS, Tiemann LK, Weintraub MN. 2014. Crop rotation complexity regulates the decomposition of high and low quality residues. *Soil Biology & Biochemistry* **78**:243–254 DOI 10.1016/j.soilbio.2014.07.027.

Meng F, Dungait JAJ, Xu X, Bol R, Zhang X, Wu W. 2016. Coupled incorporation of maize (*Zea mays* L.) straw with nitrogen fertilizer increased soil organic carbon in Fluvic Cambisol. *Geoderma* **304**:19–27 DOI 10.1016/j.geoderma.2016.09.010.

Nelson DW, Sommers LE. 1982. Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR, eds. *Methods of soil analysis, Part 2.* Madison: American Society of Agronomy, 539–579.

Peng YF, Guo DL, Yang YH. 2017. Global patterns of root dynamics under nitrogen enrichment. *Global Ecology and Biogeography* **26**:102–114 DOI 10.1111/geb.12508.

Ren FL, Misselbrook TH, Sun N, Zhang XB, Zhang SX, Jiao JH, Xu MG, Wu L. 2021. Spatial changes and driving variables of topsoil organic carbon stocks in Chinese croplands under different fertilization strategies. *Science of the Total Environment* **767**:144350 DOI 10.1016/j.scitotenv.2020.144350.

Shah SAA, Xu MG, Abrar MM, Mustafa A, Fahad S, Shah T, Shah SAA, Yang XY, Zhou W, Zhang SL, Nan S, Shi WQ. 2021. Long-term fertilization affects functional soil organic carbon protection mechanisms in a profile of Chinese loess plateau soil. *Chemosphere* **267**:128897 DOI 10.1016/j.chemosphere.2020.128897.

Silver WL, Miya RK. 2001. Global patterns in root decomposition: comparisons of climate and litter quality effects. *Oecologia* **129**:407–419 DOI 10.1007/s004420100740.

Singh K, Pandey VC, Singh B, Singh RR. 2012. Ecological restoration of degraded sodic lands through afforestation and cropping. *Ecological Engineering* **43**:70–80 DOI 10.1016/j.ecoleng.2012.02.029.

Singh K, Singh B, Singh RR. 2012. Changes in physico-chemical, microbial and enzymatic activities during restoration of degraded sodic land: ecological suitability of mixed forest over monoculture plantation. *Catena* **96**:57–67 DOI 10.1016/j.catena.2012.04.007.

Srinivasarao C, Venkateswarlu B, Lal R, Singh A, Vittal K, Kundu S, Singh S, Singh S. 2012. Long-term effects of soil fertility management on carbon sequestration in rice-lentil cropping system of the Indo-Gangetic plains. *Soil Science Society of America Journal* **76**:168–178 DOI 10.2136/sssaj2011.0184.

Strahm BD, Harpison RB, Terpy TA, Harpington TB, Adams AB, Footen PW. 2009. Changes in dissolved organic matter with depth suggest the potential for postharvest organic matter retention to increase subsurface soil carbon pools. *Forest Ecology and Management* **258**:2347–2352 DOI 10.1016/j.foreco.2009.03.014.

Tang ZS, Deng L, An H, Yan WM, Shangguan ZP. 2017. The effect of nitrogen addition on community structure and productivity in grasslands: a meta-analysis. *Ecological Engineering* **99**:31–38 DOI 10.1016/j.ecoleng.2016.11.039.

Tian K, Zhao Y, Xu X, Hai N, Huang B, Deng W. 2015. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: a meta-analysis. *Agriculture Ecosystems & Environment* **204**:40–50 DOI 10.1016/j.agee.2015.02.008.

Troeh FR, Thompson LM. 2005. *Soils and soil fertility*. Ames: Blackwell, 489.

United Nations Environment Program. 2017. The Emissions Gap Report 2017.

VandenBygaart AJ, Bremer E, McConkey BG, Ellert BH, Janzen HH, Angers DA, Carter MR, Drury CF, Lafond GP, McKenzie RH. 2010. Impact of sampling depth on differences in soil carbon stocks in long-term agroecosystem experiments. *Soil Science Society of America Journal* **75**:226–234 DOI 10.2136/sssaj2010.0099.

Wang W, Chen WC, Wang KR, Xie XL, Yin CM, Chen AL. 2011b. Effects of long-term fertilization on the distribution of carbon, nitrogen and phosphorus in water-stable aggregates in paddy soil. *Agricultural Sciences in China* **10**:1932–1940 DOI 10.1016/S1671-2927(11)60194-6.

Wang SQ, Fan JW, Song MH, Yu GR, Zhou L, Liu JY, Zhong HP, Gao LP, Hu ZM, Wu WX, Song T. 2013. Patterns of SOC and soil ^{13}C and their relations to climatic factors and soil characteristics on the Qinghai-Tibetan Plateau. *Plant and Soil* **363**:243–255 DOI 10.1007/s11104-012-1304-6.

Wang B, Liu GB, Xue S, Zhu BB. 2011a. Changes in soil physico-chemical and microbiological properties during natural succession on abandoned farmland in the Loess Plateau. *Environmental Earth Sciences* **62**:915–925 DOI 10.1007/s12665-010-0577-4.

Wang LF, Sun JT, Zhang ZB, Xu P, Shangguan ZP. 2018. Winter wheat grain yield in response to different production practices and soil fertility in northern China. *Soil & Tillage Research* **176**:10–17 DOI 10.1016/j.still.2017.10.001.

Wang WJ, Wang HM, Zu YG. 2014. Temporal changes in SOM, N, P, K, and their stoichiometric ratios during reforestation in China and interactions with soil depths: importance of deep-layer soil and management implications. *Forest Ecology and Management* **325**:8–17 DOI 10.1016/j.foreco.2014.03.023.

Wang RJ, Zhou JX, Xie JY, Khan A, Yang XY, Sun B, Zhang SL. 2020. Carbon sequestration in irrigated and rain-fed cropping systems under long-term fertilization regimes. *Journal of Soil Science and Plant Nutrition* **20**:941–952 DOI 10.1007/s42729-020-00181-6.

Xie JY, Hou MM, Zhou YT, Wang RJ, Zhang SL, Yang XY. 2017. Carbon sequestration and mineralization of aggregate-associated carbon in an intensively cultivated Anthrosol in north China as affected by long term fertilization. *Geoderma* **296**:1–9 DOI 10.1016/j.geoderma.2017.02.023.

Yang XY, Sun BH, Zhang SL. 2014. Trends of yield and soil fertility in a long-term wheat-maize system. *Journal of Integrative Agriculture* **13**:402–414 DOI 10.1016/S2095-3119(13)60425-6.

Zha Y, Wu X, Gong F, Xu M, Zhang H, Chen L, Huang S, Cai D. 2015. Long-term organic and inorganic fertilizations enhanced basic soil productivity in a fluvo-aquic soil. *Journal of Integrative Agriculture* **14**:2477–2489 DOI 10.1016/S2095-3119(15)61191-1.

Zhang ZS, Song XL, Lu XG, Xue ZS. 2013. Ecological stoichiometry of carbon, nitrogen, and phosphorus in estuarine wetland soils: influences of vegetation coverage, plant communities, geomorphology, and seawalls. *Journal of Soils and Sediments* **13**:1043–1051 DOI 10.1007/s11368-012-0571-4.

Zhang WJ, Wang XJ, Xu MG, Huang SM, Liu H, Peng C. 2010. Soil organic carbon dynamics under long-term fertilizations in arable land of northern China. *Biogeosciences* **7**:409–425 DOI 10.5194/bg-7-409-2010.

Zhang Z, Zhang X, Xu M, Zhang S, Huang S, Liang W. 2016. Responses of soil micro-food web to long-term fertilization in a wheat-maize rotation system. *Applied Soil Ecology* **98**:56–64 DOI 10.1016/j.apsoil.2015.09.008.

Zhao YW, Wang JZ, Wang SC, Wu HL, Huang SM, Lu CA. 2016. Contributions of wheat and corn residues to soil organic carbon under Fluvo-Aruic soil area-based on the modified RothC model. *Scientia Agricultura Sinica* **49**:4160–4168 (in Chinese with English abstract).