

The trend of soil organic carbon, total nitrogen, and wheat and maize productivity under different long-term fertilizations in the upland fluvo-aquic soil of North China

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Abstract Evaluating the effects of management practices on the soil organic carbon (SOC), total nitrogen (TN) and grain yields would be valuable to explain field-level variability in crop production. A 33-year field experiment on the fluvo-aquic soil of North China with six treatments in a wheat (*Triticum aestivum* L.)—maize (*Zea mays* L.) rotation was evaluated. The six treatments were: non-fertilization (CK), nitrogen (N), nitrogen–phosphorus fertilization (NP), nitrogen–phosphorus–potassium fertilization (NPK), manure and nitrogen fertilization (NM), and straw returned with nitrogen fertilizers (NS). The results showed that the content of SOC and TN significantly increased in NM treatment. Application

of inorganic fertilizers had small influence on SOC, but SOC and TN increased significantly in NM treatment over the long-term experiment. Compared to control, grain yield of wheat and maize increased two times under all treatments. The highest grain yield was detected in NM and NPK treatments. However, wheat yield was not significantly different ($P > 0.05$) between control and N treatment. Grain yields were more than doubled under fertilization for both wheat and maize, with the highest yield under the NM and NPK treatments and the lowest under CK treatment for maize and N treatment for wheat. The NP fertilization had little effect on maize yield in long-term, suggesting that potassium was not the primary limiting nutrients in the study site. Statistical analysis indicated that maize yield was significantly correlated with SOC and TN, and wheat yield was significantly correlated with SOC only. However, the relationships were stronger with TN ($r = 0.26–0.42$) than SOC ($r = 0.12–0.37$), indicating the importance of maintaining TN in agricultural soils. There was a strong positive linear correlation between carbon sequestered and carbon input ($r = 0.828$, $P < 0.01$) in the study site, indicating that the conversion rate of carbon input to SOC was 8.5 %. SOC did not reach the saturation in fluvo-aquic soil and have the potential to sequester more carbon.

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fertilization · Grain yield · Soil organic carbon · Total
nitrogen

Introduction

Agricultural management plays an important role in food security and global climate change, which requires an improved understanding on how to achieve optimal crop yields whilst minimizing the harmful effects on agro-ecosystem (Guo et al. 2012). Fertilization is the main measurement to improving crop yield and maintaining soil fertility. For example, organic manure could significantly increase soil total N and $\delta^{15}\text{N}$, at the same time, mineral NPK fertilizer and NP fertilizer significantly increased total N and slightly increased $\delta^{15}\text{N}$, whereas Phosphorus-deficient fertilization (NK) and N-deficient fertilization (PK) had no effect on soil total N (Chen et al. 2011). Beyond this, straw retention and N application improved organic C and N in soil, thus could help control greenhouse gas emissions (Malhi et al. 2011).

Nitrogen fertilizer is one of the most important management practice to increase and maintain crop production and quality in modern crop management (Fixon and West 2002; Robertson and Vitousek 2009). The crop harvest index will be reduced if the amount of nitrogen fertilizer is deficits (Salvagiotti et al. 2008). Crop response to nitrogen fertilizer involves increase carbon dioxide (CO_2) fixation and, as a consequence, aboveground and root biomass production (Tognetti et al. 2005). It leads to more crop root residue return to soil (Studdert and Echeverri'a 2000; Wilts et al. 2004).

Agricultural N management can provide sufficient N to crops. On the other hand, it could increase crop yield and minimize environmental impact of other ecosystems (Bandyopadhyay et al. 2010; Giola et al. 2012). However, Environmental problems related to the use of N fertilizer focused primarily on the effects of nitrate leaching on the groundwater and nitrous oxides emissions into the atmosphere (Galloway et al. 2004; Crutzen et al. 2008). Application of chemical fertilizers is the dominant source of N input in the crop production system (Abbasi and Tahir 2012). To meet the food demands of an increasing population in China, more mineral fertilizer N was applied into the soils, which accounts for more than one quarter of the total N fertilizer used around the world (Yu et al. 2005). Therefore, nitrogen management is a key factor in controlling the efficacy of N fertilizer in China. The deterioration of soil quality was due to usage of chemical fertilizer instead of organic amendments,

especially in China. In order to protect the environment and to relieve energy crisis, it is becoming more important to develop local abundant agricultural bio-resources (Liu et al. 2009; Zhou et al. 2011). A large amount of organic materials, such as farmyard manure, composts, poultry manure, crop residues, and green manure, have been used as sources of plant nutrients. The nutrients in organic manures are released more slowly than chemical fertilizer, which could ensure a long residual effect on crop production. It is possible to provide the same amount food with less fossil fuel-based inorganic fertilizers. The recycling of organic materials is likely to release a substantial amount of nutrient especially nitrogen into the mineral N pool, reducing fertilization costs, and providing an amount of available N that allows maintenance of crop yields (Panwar et al. 2010; Ribeiro et al. 2010; Thy and Buntha 2005).

In order to access the effect of mineral fertilizer or manure on crop yield and soil nutrient, studies have been conducted both under laboratory and field (Aulakh et al. 2000; Abbasi et al. 2007; Ahmad et al. 2008; Gopinath et al. 2008; Azeez and Van Averbeke 2010). Although Gopinath et al. (2008) found that the grain yield of wheat was higher markedly in mineral fertilizer treatment than in the treatments involving organic amendments, many other studies reported positive effects of organic substrates applied alone or in combination with inorganic fertilizers on productivity of crop (Ahmad et al. 2008; Yadvinder-Singh et al. 2009; Shah et al. 2009), and strongly encouraged application of organic materials in crop production in many places as a replacement for part or all of the mineral fertilizer used (Pinitpaitoon et al. 2011).

Although inorganic fertilizers could provide essential nutrients for crops improvement to obtain higher yields, it could lead to decrease of soil quality, such as soil acidification, soil hardening. Organic manure is not readily available and has relatively low nutrient content, but it can provides nutrients to maintain crop production (Bayu et al. 2006). Numerous studies demonstrated combined application of organic fertilizer and inorganic fertilizer could improve crop yield (Cai and Qin 2006) and SOC accrual (Kukul et al. 2009) in agricultural soils. Therefore, an integrated nutrient management program using organic manure and inorganic fertilization has been suggested as a rational strategy (Palm et al. 1997). It is commonly believed that the combination of organic and inorganic

fertilizer would increase synchrony and reduce losses by converting inorganic N into organic forms (Kramer et al. 2002). It is important to enhance the use efficiency of the fertilizers and to reduce environmental problems. However, because of economic pressure, and lack in knowledge of fertilizer management, nutrient-deficient fertilization and agroecosystem pollution by fertilization practice are still widespread in developing countries such as China. Therefore, it is necessary to compare the effects of different organic materials on sustainability of agricultural systems.

Several studies on crop productivity and soil nutrient have been conducted to assess the effects of integrated use of mineral fertilizer and organic manure on crop productivity and soil nutrient (Cai and Qin 2006; Yang et al. 2015). However, in the north of China, a few studies and little information have been reported on crop yields, SOC and total nitrogen in relation to combined application of organic materials and chemical fertilizer under long-term fertilizer of wheat-maize rotation on the heavy loamy fluvo-aquic soil. The Fluvo-aquic soil, developed from river alluvium, is widely spread in this area and accounts for 72 % of the total area, and is an important grain production base in China. Therefore, we hypothesized that combined application of mineral N and organic materials under these conditions will improve the soil conditions and thereby increase nutrient release, nutrient uptake, and ultimately crop yield. In this paper, a 33-year of long-term fertilizer on heavy loamy fluvo-aquic soil at Tianjin, China was investigated to study the effects of long-term fertilization on the trend of soil organic carbon, total nitrogen and crop yield. The overall objective of this study was to establish a reasonable fertilization system according to local conditions to improve the soil fertility, to protect soil resource, and to provide scientific basis for sustainable agricultural development on the Fluvo-aquic soil in China.

Materials and methods

Field site and experiment design

The long-term experiment was established in 1979 at Tianjin, northern China (117°60'E, 39°10'N). The study site is a warm and semi-humid continental monsoon climate. The mean annual temperature is

11.6 °C, and the active accumulated temperature (the sum of the daily temperature is over 10 °C) is about 4200 °C. The annual precipitation is 607 mm, about 80 % of which occurs from June to September. The average annual evaporation is 1736 mm.

In this study, six treatments with four replicates were selected (Table 1): treatments included: (1) non-fertilization (CK); (2) inorganic nitrogen (N); (3) inorganic nitrogen and phosphorus combination (NP); (4) inorganic nitrogen, phosphorus and potassium combination (NPK); (5) inorganic nitrogen and organic manure combination (NM); (6) inorganic nitrogen and straw combination (NS). Each plot was 16.7 m² and was isolated by cement baffle plates. Inorganic nitrogen, phosphorus and potassium fertilizers were urea, calcium superphosphate, and potassium chloride, respectively. For the NM treatment, Organic manure was dung (raw manure was mixed with garbage soil) from 1979 to 1998, and was chicken manure after 1998. The carbon, nitrogen, phosphorus and potassium contents were 367.75, 63.82, 13.22 and 16.04 g kg⁻¹ in dung, respectively, and 301.46, 23.38, 9.29 and 16.06 g kg⁻¹ in manure respectively. All organic manure, P and K fertilizers and half the N fertilizer were applied as basal fertilizers prior to winter wheat seeding. The remaining N fertilizer was applied as top dressing during the maize growing season.

The same long-term experiment with different treatments from this study has been described by Yang et al. (2015). The experiment was cultivated with a double winter wheat (*Triticum aestivum* L.)—summer maize (*Zea mays* L.) rotation system every year. Winter wheat seeds were sown in strips around October 1st at a rate of 210 kg ha⁻¹ and row space of 20 cm, and harvested in early June in the next year. The summer maize seeds were sown in holes within 1–2 days after winter wheat was harvested, and the plant density was 69,000 seeds ha⁻¹ with a 50 cm row spacing, which was harvested in late September. Winter wheat was irrigated 2–3 times and maize had no irrigation. Herbicides and pesticides were applied to control weeds and insect occurrence during the growth periods when it was needed. Crops were harvested manually by cutting straws close to the ground. Thus stubble left in the field was negligible, and roots were left in the soil. All above-ground biomass were removed from the field, and the maize roots were also removed when being plowed. Grain and straw were weighted separately after air drying.

Table 1 Annual amount of N, P, K fertilizer and organic manure applied for various fertilization treatments

Fertilizations	Wheat				Maize			
	Inorganic N (kg N ha ⁻¹)	P ₂ O ₅ (kg P ₂ O ₅ ha ⁻¹)	K ₂ O (kg K ₂ O ha ⁻¹)	Organic manure (kg ha ⁻¹) ^a	Inorganic N (kg N ha ⁻¹)	P ₂ O ₅ (kg P ₂ O ₅ ha ⁻¹)	K ₂ O (kg K ₂ O ha ⁻¹)	Organic manure (kg ha ⁻¹) ^a
CK	0	0	0	0	0	0	0	0
N	285	0	0	0	210	0	0	0
NP	285	142.5	0	0	210	0	0	0
NPK	285	142.5	71.3	0	210	0	0	0
NM	285	0	0	11,535	210	0	0	0
NS	285	0	0	Straw return ^b	210	0	0	Straw return ^b

Inorganic N fertilizer is urea, P as calcium superphosphate, K as KCl

^a In air-dried dung or chicken manure weight

^b All wheat and maize straw is returned to the soil each year

Soil sampling and analysis

Soil samples were collected from the plow layer (0–20 cm) each year in September, and each plot was randomly sampled for 5 or 6 cores. The soil samples of 6 cores were mixed thoroughly, and air dried. Subsequently, the air-dried soil samples were sieved through 0.25-mm screens, and then the sieved soil samples were stored in sealed plastic jars for analysis. The SOC content was determined by vitriol acid–potassium dichromate oxidation (Walkley and Black 1934). Total nitrogen (TN) was determined by the method described by Black (1965). Three replicates were carried out for each analysis. Basic soil properties before the long-term experiment were presented in Table 2.

Quantitative estimation of the soil carbon sequestration

Carbon accumulation rate of soil was calculated by difference subtraction.

$$S_0 = C_0 \times B_0 \times D \quad (1)$$

$$S_t = C_t \times B_t \times D \quad (2)$$

$$C = (S_t - S_0)/n \quad (3)$$

C (t ha⁻¹ year⁻¹) is carbon accumulation rate of soil; S_t (t ha⁻¹) is carbon storage of topsoil in 2014; S_0 (t ha⁻¹ year⁻¹) is carbon storage of topsoil in starting

Table 2 Basic soil properties in 1979 at Tianjin site, northern China

Soil properties	Values
Soil organic C (g kg ⁻¹)	10.96
Total N (g kg ⁻¹)	1.00
Total P (g kg ⁻¹)	1.59
Total K (g kg ⁻¹)	16.14
Available N (mg kg ⁻¹)	75.10
Olsen-P (mg kg ⁻¹)	15.80
Available K (mg kg ⁻¹)	176.6
pH (1:5 w/v water)	8.1
Bulk density (g cm ⁻³)	1.28

year; n (year) is time of long-term positioning experiment, C_0 and C_t were the SOC content (g kg⁻¹) at the start of the trial and 2014, B_0 and B_t were the soil bulk density at the beginning of the trial and 2014, D was topsoil depth (20 cm).

Estimation of soil carbon input

The crop root and its secretion, root stubble, organic manure and straw were the major C sources of soil C. Crop stalk and stubble were removed, so the organic C inputs were mainly roots, root secretion, and organic manure. Because the soil fertility and crop yields were different with different fertilizer treatments, the contents of organic carbon distributing into the root area and root secretion in soil were different.

Because of crop root and its secretion changes constantly, the conventional method, namely non-marking method, is difficult to obtain the content of carbon. By using method of C isotope, studies have shown that about 30 % SOC came from roots, including the root exfoliation, discharge and death during crop growth stage (Kuzyakov and Domanski 2002), this estimate is also widely used in the world (Chander et al. 1997; Amos and Walters 2006). Based on recorded maize straw and grain yields, carbon content in maize plants was 44.4 % (The National Agricultural Technology Extension Service Center 1994) and organic manure application, the amount of root organic carbon inputs was calculated as follow:

$$A = [(YG + YR) \times 0.444 \times 30 \% + M]/n \quad (4)$$

where A, YG and YR, M and n respectively represent the root carbon inputs ($\text{t ha}^{-1} \text{ year}^{-1}$), grain yield (t ha^{-1}), straw yield (t ha^{-1}), organic carbon inputs from manure (C, t ha^{-1}), and n fertilization time, respectively.

Data analysis

The crop yield is related with the activity of solar spot, because the activity of solar spot affects weather change (Bo and Lu 1995). Since the solar cycle is about 11 years, an 11-year period can include different weather condition. Therefore, to assess the long-term impacts of fertilization on grain yields and minimize or take out the effect of weather on the crop yield, we analyzed data for three periods (i.e., 1978–1990, 1991–2002 and 2003–2012), and each period was about 11 years (Table 4). SOC, total nitrogen, and wheat and maize grain yields under various fertilization practices were analyzed for the three periods of 1979–1990, 1991–2002 and 2003–2012 by one way ANOVA method in SPSS 13.0. Linear regression was employed to determine relationships between grain yields and soil properties, and the change trends in SOC and total nitrogen contents under various fertilizations.

Results

Soil organic carbon and total nitrogen

The SOC and TN contents under various fertilizations during 1979–2012 were shown in Fig. 1. The highest SOC and TN contents were found under the NM

fertilization, followed by NPK fertilization. There was little effect of CK, N, NP and NS treatments on SOC content, whereas NM treatment increased SOC content, particularly during 1991–2012, but, there was no significant increase of SOC under NS treatment. However, responses of TN were different to those of SOC, and there was much larger interannual fluctuations in the TN than in SOC. The TN content was the lowest under non-fertilization compared with others during the long-term experiment, followed by unbalanced fertilization (N, NP).

SOC content varies from 11.29 g kg^{-1} in CK to 13.90 g kg^{-1} in NM treatment for the first period, 11.91 g kg^{-1} in CK to 19.47 g kg^{-1} in NM treatment for the second period, and 13.21 g kg^{-1} in CK to 22.65 g kg^{-1} in NM treatment for the third period. Statistical analyses indicate that there were no significant differences in the SOC content among the CK and inorganic fertilizations (N). Significantly high SOC contents were resulted from the applications of NP, NM, NPK and NS during the period of 1979–1990. While all the fertilizations result in increases of SOC content from the period of 1991–2002 to the period of 2003–2012. Significant high SOC content resulted from the applications NM during the period of 1991–2002 and 2003–2012. At the same time, those with application of manure (NM) led to increases of the TN content. However, increases of TN are much smaller (11.4–36.2 %) than those of SOC (16.3–40.1 %). The CK, NP, NPK and NS treatments cause increase of TN by 4.4–21.2 and 6.4–19.0 % during 1991–2002 and 2003–2012, respectively (Table 3).

Crop yields

Figure 2 shows the grain yields of wheat and maize during the 33 years of experiment. The lowest yields were obtained in the non-fertilization treatment, and the highest in the NPK and NM treatments for wheat and maize. For most of years, grain yields are more than double under fertilization, compared to non-fertilization. The only exception is the NP fertilization that has little effect on maize grain yield, suggesting that potassium was not the primary limiting nutrient for maize at this site. Overall, responses of wheat grain to fertiliser treatments are different to those of maize grain, especially the trend and interannual variations. Nevertheless, both wheat and maize grains show

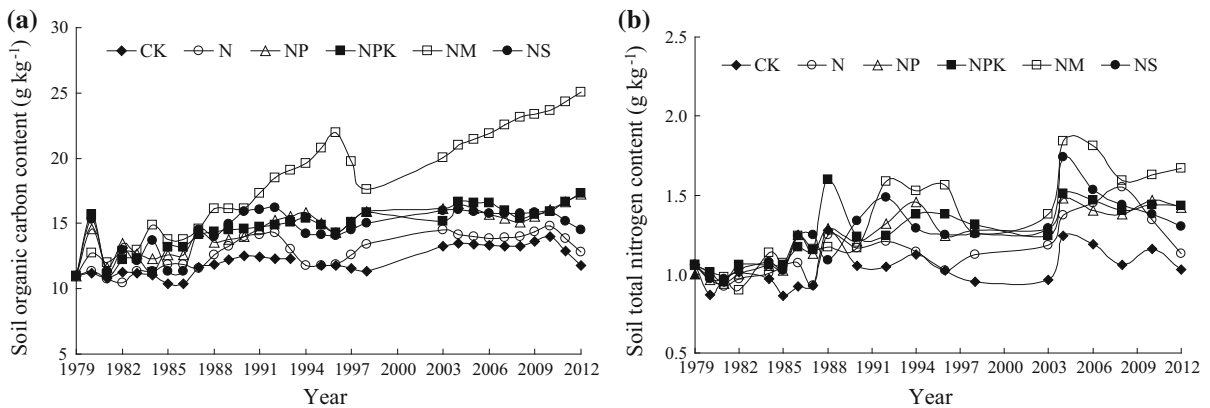


Fig. 1 Trend of soil organic carbon (a) and total nitrogen content (b) under different fertilization treatments

Table 3 Contents of soil organic carbon and total nitrogen of air-dried soil for the period of 1979–1990, 1991–2002 and 2003–2012 under various fertilizations

Treatment	1979–1990 (g kg ⁻¹)	1991–2002 (g kg ⁻¹)	2003–2012 (g kg ⁻¹)	1979–2002 Change (%)	1991–2012 Change (%)
<i>Soil organic carbon</i>					
CK	11.29b	11.91c	13.21d	5.5	10.9
N	11.77b	12.87c	14.03c	9.4	9.0
NP	13.04a	15.28b	16.04b	17.2	4.9
NPK	13.13a	15.05b	16.2b	14.6	7.7
NM	13.90a	19.47a	22.65a	40.1	16.3
NS	13.21a	14.95b	15.68b	13.2	4.8
<i>Soil total nitrogen</i>					
CK	0.99c	1.04c	1.11d	4.4	6.8
N	1.04bc	1.12c	1.34c	8.0	19.0
NP	1.09ab	1.32b	1.41bc	21.2	6.4
NPK	1.14a	1.33b	1.42bc	17.0	6.5
NM	1.09ab	1.48a	1.65a	36.2	11.4
NS	1.1ab	1.32b	1.45b	19.5	9.6

Different letters in the same column indicate that there are significant differences ($P < 0.05$) among the treatments

similar responses to various fertilizations during the first few years, but much different response during the last few years.

Wheat grain yield shows a significant correlation with the SOC and the TN, using the data collected during 1979–2012 (Fig. 3). Interestingly, wheat grain yield has a stronger correlation with TN ($r = 0.42$) than with SOC ($r = 0.37$). Statistical analyses indicated that fertilizer treatments resulted in high wheat grain yields (3544–4973 kg ha⁻¹) during the period of 1979–1990 (Table 4), which were significantly

different to that (1800 kg ha⁻¹) from non-fertilization. While most fertilization continues to lead low grain yields of wheat during 1991–2002 with exception of NM and NPK treatments (5199 and 5027 kg ha⁻¹). During 2003–2012, all treatments were low in wheat yield. For maize, fertilizations (except N) lead to much higher grain yields (5954–6309 kg ha⁻¹) than non-fertilization (2449 kg ha⁻¹) during 1979–1990. Most fertilization continued to lead low maize grain yields than during 1991–2002, especially the treatment with N, maize

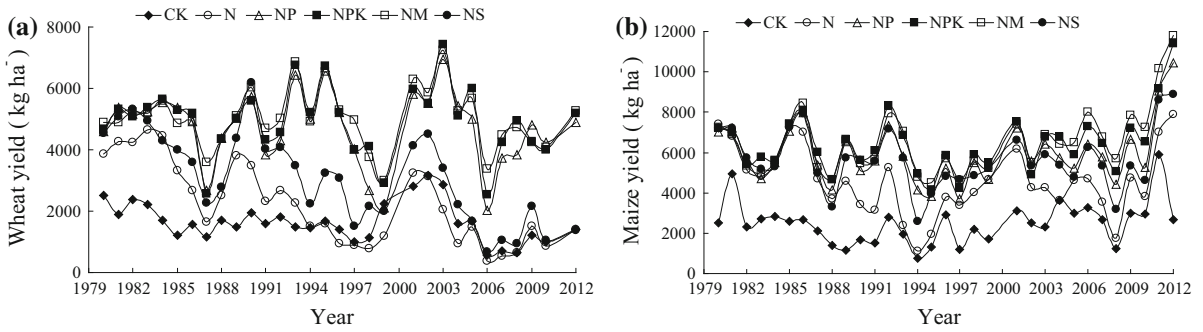
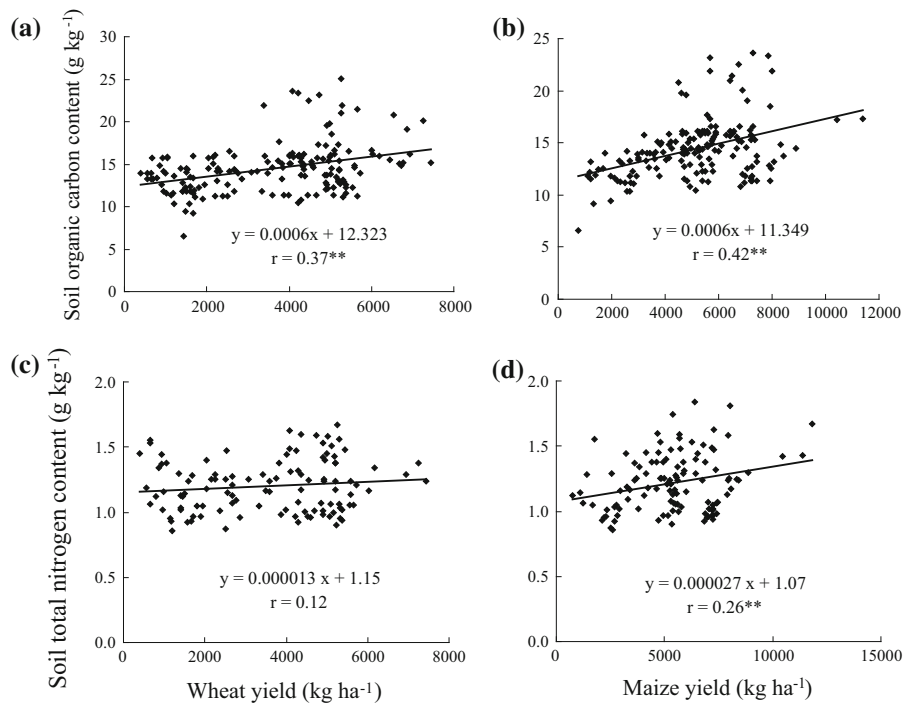


Fig. 2 Grain yields of wheat (a) and maize (b) under different fertilizations from 1979 to 2012

Fig. 3 Linear correlations between grain yield of wheat and maize with SOC and the total nitrogen shown are Pearson correlation coefficients. Significant correlations are marked with one ($P < 0.05$) and two ($P < 0.01$) asterisks



yield decreased by 33.3 %. However, during 2003–2012, fertilization continues to lead high maize yield. Moreover, application of NM and NPK fertilizers results in the highest maize grain yields (7739 and 7253 kg ha⁻¹), and NM and NPK treatments were not significantly different.

In this study, long-term cropping practices without fertilization treatment remains stable during 1979–2002 and causes decline (28.2 %) during 2003–2012 in wheat yields (Table 4). The same treatment causes decline (18.5 %) during 1979–2002 and causes increase (32.0 %) during 2003–2012 in maize yields. In the unbalanced fertilization treatment,

N treatment is found the largest decrease (33.3–47.2 %), NP treatment is decrease only 3.0–11.6 % (In addition to during 1991–2012 in maize yield). Which is probably caused by decline of some elements (e.g., P) during the long-term experiment.

Discussion

Trends of grain yield

There has been evidence that nitrogen fertilization can increase maize yields (Dapaah and Vyn 1998; da Silva

Table 4 Wheat and maize grain yields for the period of 1979–1990, 1991–2002 and 2003–2012 under various fertilizations

Treatments	1979–1990 (kg ha ⁻¹)	1991–2002 (kg ha ⁻¹)	2003–2012 (kg ha ⁻¹)	1979–2002 Change (%)	1991–2012 Change (%)
<i>Wheat</i>					
CK	1800d	1802c	1294b	0.1	-28.2
N	3544c	1871c	1096b	-47.2	-41.4
NP	4909a	4688a	4549a	-4.5	-3.0
NPK	4924a	5027a	4862a	2.1	-3.3
NM	4973a	5199a	4929a	4.6	-5.2
NS	4303b	3135b	1614b	-27.2	-48.5
<i>Maize</i>					
CK	2449c	1996d	2755e	-18.5	32.0
N	5481b	3657c	3890d	-33.3	6.4
NP	6030a	5329ab	5743b	-11.6	7.8
NPK	6309a	5841a	6498a	-7.4	11.2
NM	6166a	5819a	6927a	-5.6	19.0
NS	5954ab	5143b	5226c	-13.6	1.6

Different letters in the same column indicate that there are significant differences ($P < 0.05$) among the treatments

et al. 2005; Goncalves et al. 2007; Duete et al. 2008). These results suggest that fertilization practice should include those non-limiting elements in order to maintain sustained high production. While the balanced fertilization of NPK can maintain sustained grain yields, such practice does not seem to be able to maintain high grain yields for both wheat and maize over a long period. Long-term NPK fertilization probably causes acidification and degradation of soil structure (Graham et al. 2002; Malhi et al. 2000; Edmeades 2003; Zhang et al. 2008). Overall, addition of manure leads to high yields over time. These results suggest that long-term application of manure is a favorable practice. For the maize cropping, grain yield clearly shows an increasing trend in the treatments with application of manure. Balance NPK application at high yield appears favorable for maize cropping practice at this site. There is no significant difference in grain yield between the NPK and NM during the all period.

Trends of SOC and TN

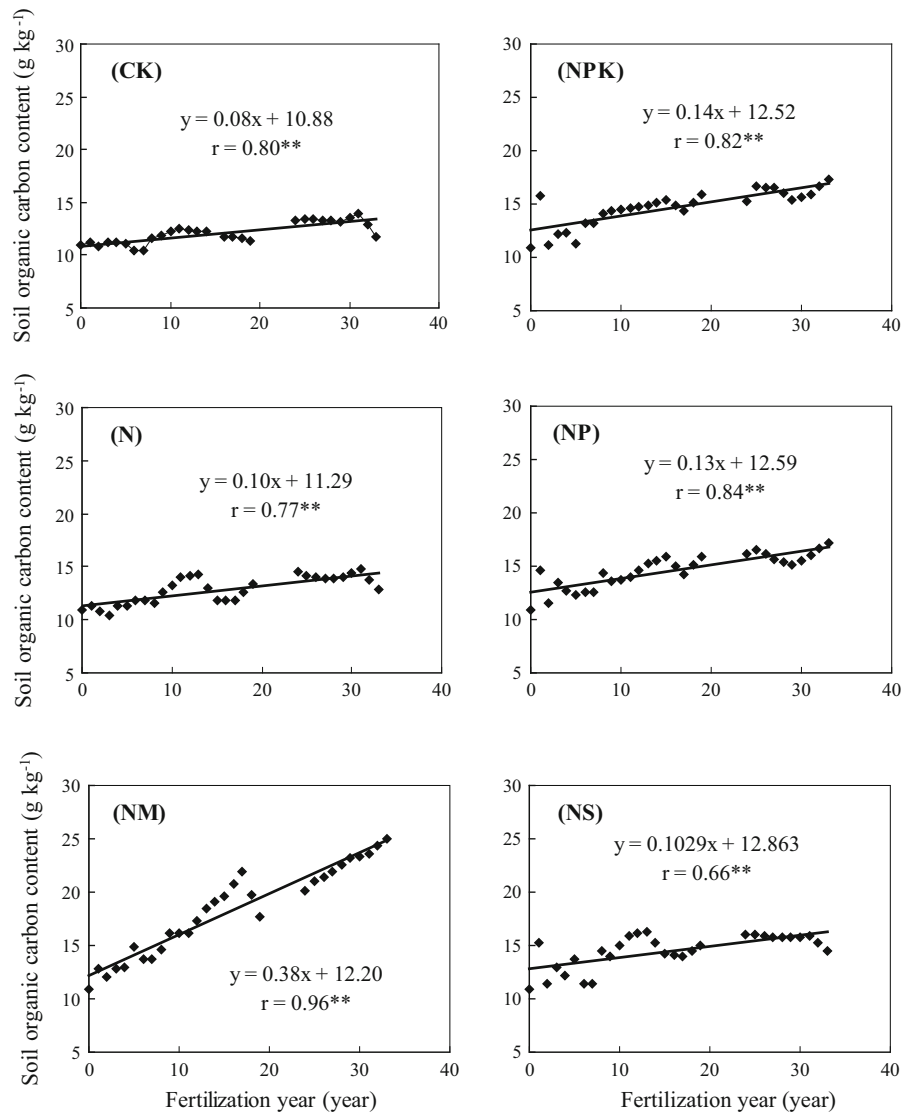
Application of organic material (i.e., manure and straw) with inorganic fertilizers increased SOC content over long-term cropping as shown in Fig. 4. Several previous studies have reported similar effects of manure and

inorganic fertilizer applications on SOC (Rudrappa et al. 2006; Liang et al. 2009; Hao et al. 2013). Our analyses indicate that application of balanced inorganic fertilizers with or without manure or straw can also significantly increase SOC content over the long term, including unbalanced fertilization treatments (CK, N, PK).

Figure 5 presents the linear changes in TN under different fertilizations from 1979 to 2012. While all treatments show increasing trends in TN over the 33 years, NM treatment shows a modest increase (0.018 g kg⁻¹ year⁻¹) compared others. However, an early study also shows significant decline in the CK fertilization under long-term residue mulching in tropical area (Lal 1997).

In the study, application of organic manure or straw can increase SOC contents, at the same time, the application of inorganic fertilizer also can slightly increase the content of SOC, particularly with the balanced NPK applications though soil total nitrogen, containing 95 % of soil organic nitrogen. Results indicated that the rate of carbon cycle was different with that of nitrogen cycle in the agro-ecosystem in the fluvo-aquic soil, suggesting complex implications of the climate–agriculture interaction and feedbacks. On the one hand, agricultural practices such as fertilization enhance sequestration of atmospheric CO₂ as SOC, contributing to the mitigation for climate

Fig. 4 Annual change in SOC after fertilizations for different treatments. Values shown are Pearson correlation coefficients. Significant correlations are marked with *one* ($P < 0.05$) and *two* ($P < 0.01$) asterisks



change. On the other hand, high yields associated with fertilizations reduce TN contents, leading to low soil fertility and providing negative feedback to sustainable agriculture. Thus, maintaining TN through applications of manure is important for both the sustainable agriculture and carbon storage.

Relations between grain yields and SOC, TN

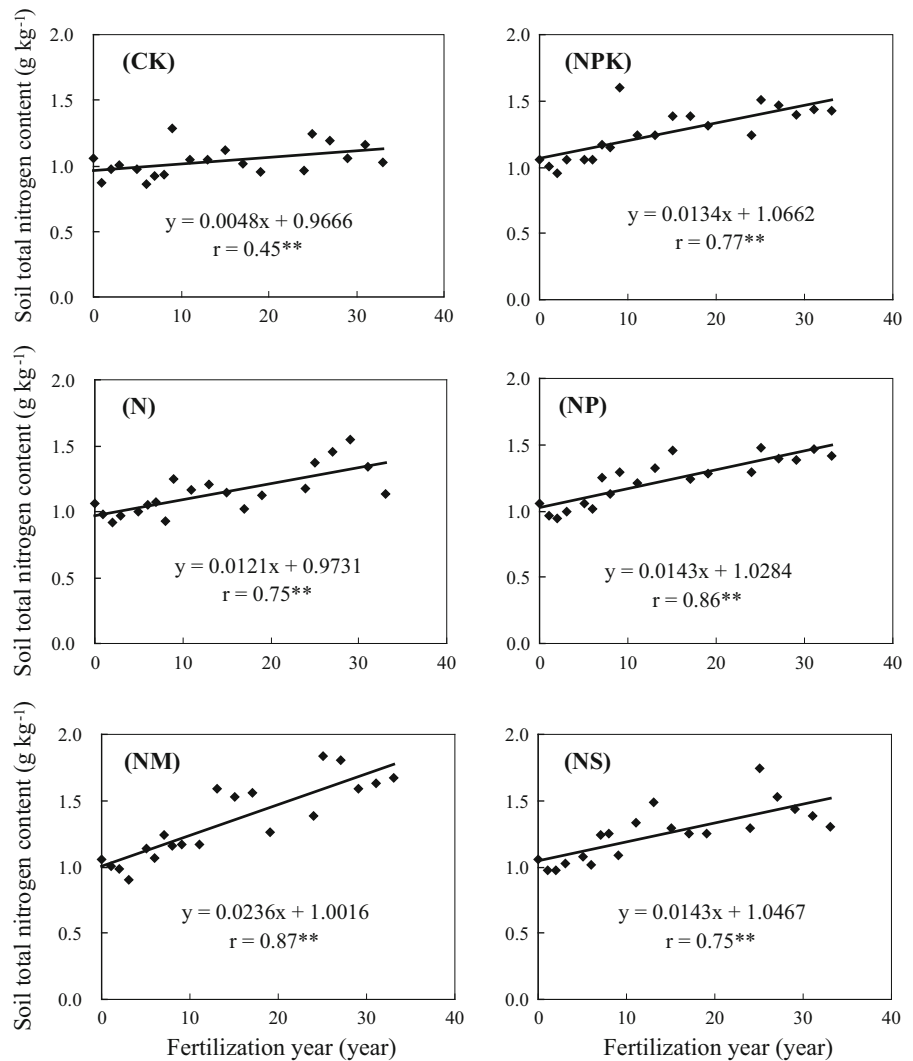
In this study, over the long-term experiment, maize grain yield shows weaker relationships with SOC and TN than wheat grain yield. Maize yield has no relationship with the TN but has a significant correlation with the SOC. Previous studies have also

showed that soil nitrogen is the one of the key factors limiting agricultural productivity in the semi-humid area (Salinas-Garcia et al. 1997; Cai and Qin 2006; Abril et al. 2007; Zhang et al. 2008).

Soil organic carbon sequestered rate and storage response relation

Figure 6 shows the SOC sequestered rate during 33 years of experiment. Clearly, the accumulation of SOC is found in the all treatments. The highest sequestration rate of SOC is found under the NM ($0.41 \text{ t ha}^{-1} \text{ year}^{-1}$) treatment fertilization and the lowest is the non-fertilization ($0.06 \text{ t ha}^{-1} \text{ year}^{-1}$).

Fig. 5 Annual change in soil total nitrogen after fertilization for different treatment. Values shown are Pearson correlation coefficients. Significant correlations are marked with one ($P < 0.05$) and two ($P < 0.01$) asterisks



There was a strong positive linear correlation between SOC sequestered and carbon input ($r = 0.860$, $P < 0.01$) in the upland fluvo-aquic soil. Sequestration rate of SOC increased with increasing carbon inputs, which indicates that the upland fluvo-aquic soil research still has a potential for carbon sequestration.

The relationship between organic carbon sequestration and carbon input can be shown by the following equation:

$$Y = 0.0849x - 0.0034$$

where x ($t \text{ ha}^{-1} \text{ year}^{-1}$) represents as carbon input; Y ($t \text{ ha}^{-1} \text{ year}^{-1}$) is organic carbon sequestration; the slope of the correlation equation indicates the change

of the organic carbon input quantity and the organic carbon balance in a unit; the interception of equation represents as the basic carbon input when the soil carbon sequestration is zero.

The result of this study showed that it is about 8.5 % of input carbon, which was transformed to Fluvo-aquic SOC in 33 years, and to maintain the initial organic carbon level (10.96 g kg^{-1}) of this experiment site, the basic input carbon is about 0.04 t ha^{-1} .

Our study shows that the relationship between the SOC storage and input during 33 years of various fertilizations. SOC storage shows a significant positive linear correlation ($r = 0.828$) with the carbon input (Fig. 7), SOC did not reach the saturation in the fluvo-

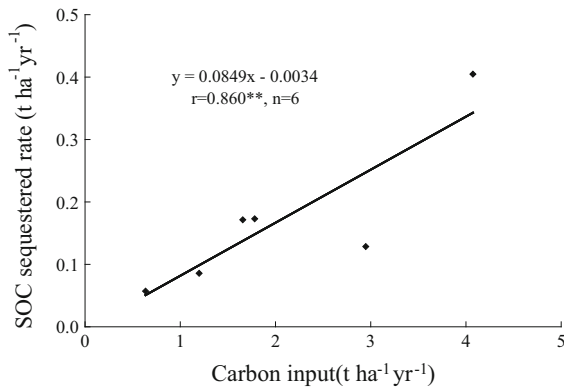


Fig. 6 Relationship between soil organic carbon (SOC) input and carbon sequestered rate under long-term different fertilizations. Values shown are Pearson correlation coefficients. Significant correlations are marked with *one* ($P < 0.05$) and *two* ($P < 0.01$) asterisks

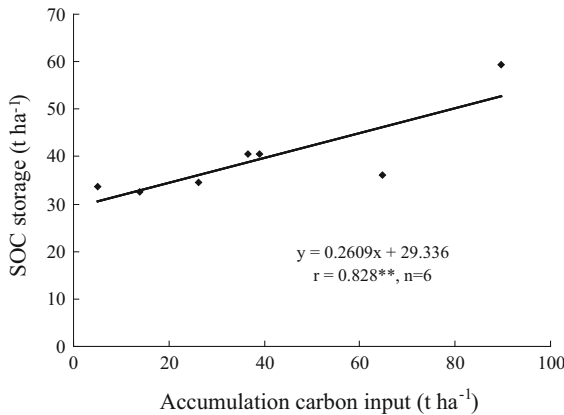


Fig. 7 Relationship between soil organic carbon (SOC) and cumulative carbon input under long-term fertilization systems. Values shown are Pearson correlation coefficients. Significant correlations are marked with *one* ($P < 0.05$) and *two* ($P < 0.01$) asterisks

aquic soil and have the potential to sequester more carbon. Similar finding has been reported by Kong et al. (2009). SOC storage increases from 13.94 to 64.85 t ha⁻¹. The highest storage of SOC was found under the NM treatment. Thus, the application of manure fertilizer can increase the SOC storage.

The results of this study revealed that conversion efficiency in fluvo-aquic soil significantly lower than black soil in the northeast China and slightly higher than red soil in the southeast China, probably because of low temperature and humidity. Cool and dry

environment slows down the microbial activity and SOC turnover (Diekow et al. 2005; Yan et al. 2007; Zhang et al. 2012). This study shows that the fluvo-aquic soils in the northeast china needs at least 0.04 t ha⁻¹ carbon input annually to maintain SOC, which has important guiding significance for the agricultural production in the sustainable development of fertilization and environmental friendly.

Conclusion

In this study, we studied the trend of SOC, TN, and crop yields in the fluvo-aquic soil during 33 years of cropping with wheat–maize rotations in the northern China. The results show that long-term applications of fertilizer result in a significant increase in the SOC and TN contents. The largest increases of SOC and TN correspond to the highest rate of NM fertilization treatment, but non-fertilizer treatment lead to slight increasing trend for SOC and TN. Therefore, fertilization is one of the most important measures maintaining soil SOC and total nitrogen.

Because the fertilizer requirement regularity is different between wheat and maize, there are large differences in the response of grain yield to various fertilizations between wheat and maize. Applications of combined manure and inorganic fertilizers led to the highest grain yields for both wheat and maize, followed by balance fertilization of NPK treatment, but there was no significant difference between them. Long-term cropping practices without fertilization or only N fertilization cause low grain yields, especially the only application of nitrogen fertilizer treatment, the yield was lowest, which is probably due to soil acidification in association with continuous application of N fertilizers. While the balanced fertilization of NPK can increase grain yields, such practice is not able to maintain high grain yields for both wheat and maize over a long period. Grain yield has a significant correlation with SOC and TN. Overall, maize grain yield shows stronger relationships with the soil SOC and total nitrogen than wheat.

There was a strong positive linear correlation between carbon sequestered and carbon input ($r = 0.828$, $P < 0.01$) at this site, indicating that the conversion rate of carbon input to SOC was 8.5 %. SOC did not reach the saturation in fluvo-aquic soil and have the potential to sequester more carbon.

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