Soil fertility and crop yield after manure addition to acidic soils in South China

Andong Cai · Wenju Zhang · Minggang Xu · Boren Wang · Shilin Wen · Syed Atizaz Ali Shah

Abstract In agro-ecosystems, the relationship between soil fertility and crop yield is mediated by manure application. In this study, an 8-year field experiment was performed with four fertilizer treatments (NPK, $NPKM_1$, $NPKM_2$, and $NPKM_3$), where NPK refers to chemical fertilizer and M_1, M_2, and M_3 refer to manure application rates of 15, 30, and 45 Mg ha^{-1} $year^{-1}$, respectively. The results showed that the NPKM ($NPKM_1$, $NPKM_2$, and $NPKM_3$) treatments produced greater and more stable yields (4.95–5.45 Mg ha^{-1} and 0.59–0.75) than the NPK treatment (4.01 Mg ha^{-1} and 0.50). Crop yields under the NPKM treatments showed two trends, with a rate of decrease of 0.48–0.83 Mg ha^{-1} $year^{-1}$ during the first 4 years and a rate of increase of 0.10–0.25 Mg ha^{-1} $year^{-1}$ during the last 4 years. The soil organic carbon (SOC) significantly increased under all treatments. The estimated annual SOC decomposition rate was 0.35 Mg ha^{-1} $year^{-1}$ and the equilibrium SOC level was 6.22 Mg ha^{-1}. Soil total nitrogen (N), available N, total phosphorus (P) and available P under the NPKM treatments increased by 0.15–0.26, 15–33, 0.17–0.66 and 45–159 g kg^{-1}, respectively, compared with the NPK treatment. Manure application mainly influenced crop yield by affecting the soil TN, available N, and available P, which accounted for up to 64% of the crop yield variation. Taken together, applying manure can determine or at least improve the effects of soil fertility on crop yield in acidic soils in South China.

Keywords Manure · Crop yields · Nutrient efficiency · Soil fertility · Acidic soil

Introduction

Improving both soil fertility and crop yield is a two-pronged challenge that is important with respect to the large, increasing population of China. Crop yields in China have increased 3–4 fold from 110 to 483 million megagrams during the past 50 years (FAO 2011). This increase is due to increased soil productivity, which has allowed China to feed 22% of the global population using only 7% of its arable land area (Zhang 2011; Fan et al. 2012). However, crop yields have also tended to decrease or remained stagnant in low-soil fertility regions of China during the past 10 years; these regions have undergone human-induced decreased soil fertility (Fan et al. 2012). Decreased soil fertility is as old as agriculture itself, and its impact on human food production and the environment have become more serious than ever before due to its extent and intensity. As such, achieving high

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crop yields under low soil fertility is difficult (Zhang et al. 2009; Tsozué et al. 2015).

Soil fertility is most commonly defined by the ability of the soil to receive and store soil nutrients and to create a favourable environment for plant root growth and function. Most studies have focused on soil organic carbon (SOC), which is an indicator of ample soil fertility with respect to the control of crop yields (Kukal et al. 2009; Tian et al. 2016). A strong relationship exists between crop production and SOC stocks (Lal 2010; Kong et al. 2014). Increasing the root zone SOC stock of cropland soils throughout the world by one Mg ha^{-1} can enhance crop productivity by 20–40 kg ha^{-1} for wheat and by 200–300 kg ha^{-1} for maize (Lal 2010). Kong et al. (2014) reported that increases in SOC stocks of one Mg ha^{-1} can increase crop yields from 66.9 Mg ha^{-1} in Changpin to 495.2 Mg ha^{-1} in Xinji, 419.2 Mg ha^{-1} in Hengshui, and 914.2 Mg ha^{-1} in Zhengzhou regions of China. The data from Australia indicated a decline in yield of wheat with depletion, increase in yield with accretion, and a stable yield of 2.75 Mg ha^{-1} with a steady-state level of the SOC stock (Farquharson et al. 2003). Thus, the SOC stock level is an essential determinant of high and sustainable crop yields.

Rational fertilization, especially manure addition, is among the most important measures for maintaining soil fertility and sustainable crop yields. The application of manure can provide not only extra organic carbon but also major nutrients via mineralization for plant use and uptake (Singh 2004; Cai et al. 2016). While the short-term effects of manure application on soil nutrients are well known, the long-term effects of manure application on the relationship between soil fertility and crop yields may be complicated. Changes in soil fertility can take several years because soil fertility cannot be critically examined by short-term experiments (Dawe et al. 2003). Therefore, long-term experiments are needed to understand the impact of soil fertility and to consider future strategies for soil fertility (Fan et al. 2008; Hijbeek et al. 2016). An analysis of the literature demonstrated that long-term manure application enhanced soil available phosphorus (P), potassium (K), and organic carbon contents, and resulted in deferred nitrogen (N) availability (Diacono and Montemurro 2010). Most studies only focus on individual soil nutrient changes that cause crop yield changes (Shen et al. 2007; Gao et al. 2015). Therefore, a comprehensive study is needed to

understand the underlying mechanisms of different soil fertility indexes on crop yields long-term.

The sustainable yield index (SYI) was considered for measuring sustainability of a cropping system under a set of management practices (Singh 1990). In the concept of SYI, low values of standard deviation suggest sustainability of the system. Subtropical arable soils in China cover approximately 446,890 km^2, which is approximately 4% of the world's subtropical arable land surface, and 37% of the arable regions in China and these soils support 22.5% of the population of China (Zhao 2002). The acidification of these regions restricts the growth of crops. Therefore, the objectives of this research were to (1) quantify the crop yield and soil fertility trends for different fertilization treatments in acidic soils and (2) identify the links between crop yield and soil fertility (explanatory variable) using manure in acidic soils in South China.

Materials and methods

Study site and initial soil properties

A long-term fertilization experiment was initiated in 2009 at the experimental station at the Chinese Academy of Agricultural Sciences, Qiyang (26°45′N, 111°52′E; 120 m in altitude), Hunan Province, China. The climate was subtropical humid monsoon, the average annual precipitation was 1408 mm, the average temperature was 18.1 °C, and the annual effective accumulated temperature (> 10 °C) was 4947 °C. The soil type was classified as a Eutric Cambisol (FAO 2006) as well as a Red soil according to the Chinese soil classification system and had a higher clay content (43.86%). The initial (2009) topsoil (0–0.20 m) had a total SOC level of 7.16 g kg^{-1}; a total N (TN) level of 0.96 g kg^{-1}; a bulk density (BD) of 1.18 kg m^{-3}; a pH (H$_2$O, 5:1 soil to water ratio) of 4.93; and available N, P and potassium (K) levels of 61.49, 10.71, and 303.39 mg kg^{-1}, respectively.

Experimental design and crop management

The long-term fertilization experiment consisted of four fertilizer treatments (Table 1). The fertilizer treatments were arranged in a randomized design

Table 1 Description of nutrient inputs from chemical fertilizers and organic manure at the long-term experimental site in this study

Treatment	Chemical fertilizer (kg ha^{-1} year^{-1})			Pig manure (kg ha^{-1} year^{-1})				Total nutrient (kg ha^{-1} year^{-1})		
	N	P	K	Manure	N	P	K	N	P	K
NPK	225	32.7	62.2	0	0	0	0	225	32.7	62.2
NPKM$_1$	180	32.7	62.2	15,000	45	36	22.5	225	68.7	84.7
NPKM$_2$	135	32.7	62.2	30,000	90	72	45	225	104.7	107.2
NPKM$_3$	90	32.7	62.2	45,000	135	108	67.5	225	140.7	129.7

and consisted of three replicates. Each plot was 13 × 13 m in size and was separated by cement plates that were approximately 0.20 m above the soil to avoid water mixing among the plots. The annual rainfall was concentrated in May to July, which was prone to flooding the soil. Each replicate was isolated by a 1 m border row and the cropping system was a single cropping system (maize). Maize seeds, the Yedan 13 variety, were sown in early April and harvested in early July. The specifications for planting included 16 rows of maize per plot (row distance of 0.6 m, planting distance of 0.25 m). No irrigation was applied to the maize plants because the plots received large amounts of annual rainfall during the experimental period. The pesticide was carbofuran, which was applied to control maize borers before the heading stage. The herbicide was glyphosate, which was applied to control grassy weeds (such as *Digitaria sanguinalis* (L.) Scop) during the growing season.

The following four fertilizer treatments were designed according to common local practices (Table 1): (1) N, P, and K chemical fertilizer (NPK); (2) chemical fertilizer (NPK) combined with 15 Mg ha^{-1} manure (NPKM$_1$); (3) chemical fertilizer (NPK) combined with 30 Mg ha^{-1} manure (NPKM$_2$); and (4) chemical fertilizer (NPK) combined with 45 Mg ha^{-1} manure (NPKM$_3$). The N, P and K minerals were applied as urea, calcium superphosphate and potassium chloride, respectively. Pig manure was acquired directly from a pig farm. The pigs were fed corn flour, which added a small feed additive. The fresh pig manure contained 70% water. The pig manure nutrient contents were empirically measured, and the average composition was as follows: (1) 413.2 g kg^{-1} C (on a dry weight basis), (2) 3.0 g kg^{-1} N, (3) 2.4 g kg^{-1} P, and (4) 1.5 g kg^{-1} K (on a fresh weight basis). The application rate of N was 225 kg ha^{-1} year^{-1} and was the same for each

treatment. Thus, based on the pig manure nutrient contents and application rates, the application of mineral N were 180, 135, and 90 kg ha^{-1} in the NPKM$_1$, NPKM$_2$, and NPKM$_3$ treatments, respectively. The application of mineral P and K for each plot was 32.7 and 62.2 kg ha^{-1}, respectively. Thirty percent of the mineral fertilizer was applied before sowing, and 70% was applied as topdressing; however, the entire amount of manure was applied into the soil by rotary tillage.

Sampling and analysis

Soil samples were collected annually from the cultivated horizon (0–0.20 m) after maize harvest. Five to 10 0.05-m-diameter soil cores were randomly sampled from each plot, after which the samples were thoroughly mixed and air-dried. The air-dried soil was then sieved through a 2-mm screen to determine the soil pH (H2O, 5:1 soil to water ratio). To measure the soil nutrients, the subsamples were crushed and passed through a 0.25-mm sieve. The SOC was measured in triplicate in accordance with the wet oxidation method by vitriol acid potassium dichromate oxidation with concentrated H_2SO_4 (Page et al. 1982), and TN, total P, and total K were measured in accordance with the methods of Black (1965), Murphy and Riley (1962), and Knudsen et al. (1982), respectively. Available N was measured in accordance with the methods of Lu (2000), and available P (Olsen-P) and available K were determined in accordance with the Olsen-P method (Olsen 1954) and the methods of Page et al. (1982), respectively. Soil BD was measured with an iron ring (Lu 2000). Grains and straws from each treatment were air dried, threshed, and then weighed. The water content of the grains and straws was approximately 14%. The grain and straw samples were digested in concentrated H_2SO_4 and analysed for N by

micro-Kjeldahl distillation (Yoshida et al. 1971). The subsamples were digested in a tri-acid mixture (HNO_3:$HClO_4$:H_2SO_4 at a 3:1:1 ratio) and analysed for P by a colorimeter and for K by an atomic absorption spectrophotometer (Nelson et al. 1996).

The SOC content (g kg^{-1}) was converted to SOC stock (Mg ha^{-1}) using the following equation (Lal and Bruce 1999):

$$SOC_{stock} = SOC_{content} \times d \times BD \times 10 \qquad (1)$$

where d and BD are the depth of the soil layer (0.20 m) and the soil dry BD (kg m^{-3}), respectively, and 10 is a conversion coefficient.

Estimation of carbon (C) inputs

The C input values included plant residues (plant roots and stubble) plus returned manure. The harvestable C biomass was estimated according to the harvestable aboveground straw biomass and yields and the C content from the straw biomass and yields using the following equation:

$$C_{biomass} = Y_{yields} \times C_{yields} + Y_{straw} \times C_{straw} \qquad (2)$$

where Y_{yields} and Y_{straw} are crop yields (Mg ha^{-1}) and straw biomass (Mg ha^{-1}), respectively, and C_{yields} and C_{straw} are the C content of the crop yield (g kg^{-1}) and the C content of the straw biomass (g kg^{-1}), respectively.

The annual C input (C_{input}, Mg ha^{-1}) was estimated from the root biomass C (C_{root}, Mg ha^{-1}) and stubble ($C_{stubble}$, Mg ha^{-1}), both of which were incorporated into the topsoil with the amount of manure (C_{manure}, Mg ha^{-1}) applied in accordance with the methods of Zhang et al. (2012) as follows:

$$C_{input} = C_{root} + C_{stubble} + C_{manure} \qquad (3)$$

$$C_{root} = R_{bg} \times C_{biomass} \qquad (4)$$

$$C_{stubble} = R_{stubble} \times C_{biomass} \qquad (5)$$

where R_{bg} is the ratio of the annual underground C from crops to aboveground biomass C, which was estimated to be 30% (Kundu et al. 2007), and $R_{stubble}$ is the ratio of stubble incorporated into the soil to aboveground biomass.

Data processing and relationship between crop yield and soil fertility

We explored the trends in the crop yield and different soil fertility indexes under different fertilizer treatments. Different analysis models were chosen based on the experimental data, and fitting processes were performed with SigmaPlot 10.0. The quantitative assessment of agricultural practice sustainability developed by Singh (1990) was adopted to study the comparative performance of different fertilizer treatments. The sustainable yield index (SYI) was used to assess the effects of agricultural practices on crop yield sustainability. When the standard deviation of the yield is high, the value of SYI will be closer to 0. Because some of these variables were correlated, a stepwise method was used to select and keep significant variables. Structural equation modelling (SEM) constitutes a formal statistical method for representing and testing direct and indirect relationships and the partial contributions of correlated explanatory variables (Brown 1997; MacKinnon et al. 2002). Furthermore, SEM has not been used for crop yield from subtropical arable soils in China. Therefore, SEM was performed to explore both the links between the crop yield and these statistically significant variables (soil fertility) by applying manure. The results of the analysis of variance showed that all the variables significantly affected the crop yield and exogenous variables. SEM was conducted with the Amos package using SPSS.

Results

Crop yields and straw biomass

The average crop yields and straw biomass of maize are summarized in Table 2. NPK resulted in 4.01 Mg ha^{-1} crop yield and 2.63 Mg ha^{-1} straw biomass; both were the lowest among the treatments. Compared with NPK, NPKM$_2$ and NPKM$_3$ significantly increased the crop yield and straw biomass by 35–36 and 43–45%, respectively. Regarding the NPKM (NPKM$_1$, NPKM$_2$, and NPKM$_3$) treatments, no significant differences were observed between the crop yield and straw biomass; however, regarding the yield and straw biomass sustainability, the SYI and straw biomass index (SSI) were consistently higher for

Table 2 Summary of crop yields with straw biomass and sustainability indexes under various fertilization treatments at the long-term experimental site in this study

Treatments	Yield				Straw biomass			
	Y^a	Sd^b	Y_{max}^c	SYI^d	S^a	Sd^b	S_{max}^c	SSI^e
NPK	4.01 b	1.20	5.57	0.50	2.63 b	0.83	3.55	0.51
NPKM$_1$	4.95 ab	0.54	5.84	0.75	3.33 ab	0.48	4.11	0.69
NPKM$_2$	5.45 a	1.15	7.28	0.59	3.76 a	0.45	4.29	0.77
NPKM$_3$	5.40 a	1.06	7.07	0.61	3.82 a	0.67	4.56	0.69

[a]Y and S stand for the average yield and straw biomass (Mg ha^{-1}), respectively. Different lowercase letters after the numbers indicate significant differences at $P \leq 0.05$ within each fertilizer treatment group according to Duncan's test

[b]Sd stands for the standard deviation of the yields during the 8-year experimental period

[c]Ymax and Smax stand for maximum yield and straw biomass, respectively, recorded during the 8-year experimental period

[d]SYI stands for the sustainable yield index for a given treatment and is calculated as SYI = (Y − Sd)/Y$_{max}$

[e]SSI stands for the sustainable straw biomass index for a given treatment and is calculated as SSI = (S − Sd)/S$_{max}$

the NPKM treatments than for the NPK treatment. Under the NPKM$_1$ and NPKM$_2$ treatments, the SYI (0.75) and SYI (0.77), respectively, were higher than those for the other fertilizer treatments.

The data regarding the crop yield and straw biomass in conjunction with annual fertilization are presented in Fig. 1. The crop yields showed a decreasing trend in response to NPK, with the rate of 0.48 Mg ha^{-1} year^{-1}. The same trend was found in all the treatments for straw biomass. The decreasing rates of straw biomass recorded for NPKM (0.16–0.22) were lower than those for NPK (0.30) and slowed the decrease in straw biomass. However, the crop yield after NPKM treatment showed two segments that exhibited opposing trends during the fourth year. During the first 4 years, the crop yields were generally decreasing, with rates of 0.48–0.83 Mg ha^{-1} year^{-1}; however, during the subsequent 4 years, the crop yield rates increased and were 0.10–0.25 Mg ha^{-1} year^{-1}.

Dynamic changes in SOC and responses to C input

The SOC contents tended to increase throughout the duration of the experiments for all the treatments, indicating that the soil could potentially sequester more C (Fig. 2). NPK had the lowest SOC contents. The results of the linear regression analysis indicated that a significant increasing trend occurred at the rate of 0.13 g kg^{-1} year^{-1} with NPK. However, a non-linear regression was observed for the NPKM treatments, suggesting that the rates of soil C sequestration

decreased as time progressed. The results from the non-linear regression analysis indicated that the SOC content could reach an equilibrium value with the NPKM treatments under the existing management styles, as values of 8.97 g kg^{-1} (NPKM$_1$) to 9.81 g kg^{-1} (NPKM$_3$) were recorded. There was an exponential relationship between soil C sequestration and C input, suggesting that soil C sequestration efficiency declined with the increasing C input gradient (Fig. 3). According to the exponential regressions, the estimated SOC decomposition rate was 0.35 Mg ha^{-1} year^{-1} and the SOC storage equilibrium level was 6.22 Mg ha^{-1} under all treatments.

Changes in soil nutrition

Changes in soil TN, available N, available P, available K and pH are shown in Fig. 4. The soil TN under the NPKM$_2$ and NPKM$_3$ treatments showed significant increasing trends throughout the study period, with increasing rates of 0.02–0.03 g kg^{-1} year^{-1}. The soil available N and P also showed significant increasing trends in all the treatments (except available P in NPK), with increasing rates of 1.30–4.26 and 5.59–18.84 mg kg^{-1} year^{-1}, respectively. Compared with the NPK treatment, the NPKM treatments maintained higher levels of soil TN, available N, and available P. However, the soil available K tended to decrease in the NPK, NPKM$_1$, and NPKM$_2$ treatments; these decreasing rates ranged from 13.84 to 123.03 mg kg^{-1} year^{-1}. The application of mineral

Fig. 1 Changes in maize yields (Mg ha^{-1}) under various fertilization treatments at the long-term experimental site. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively
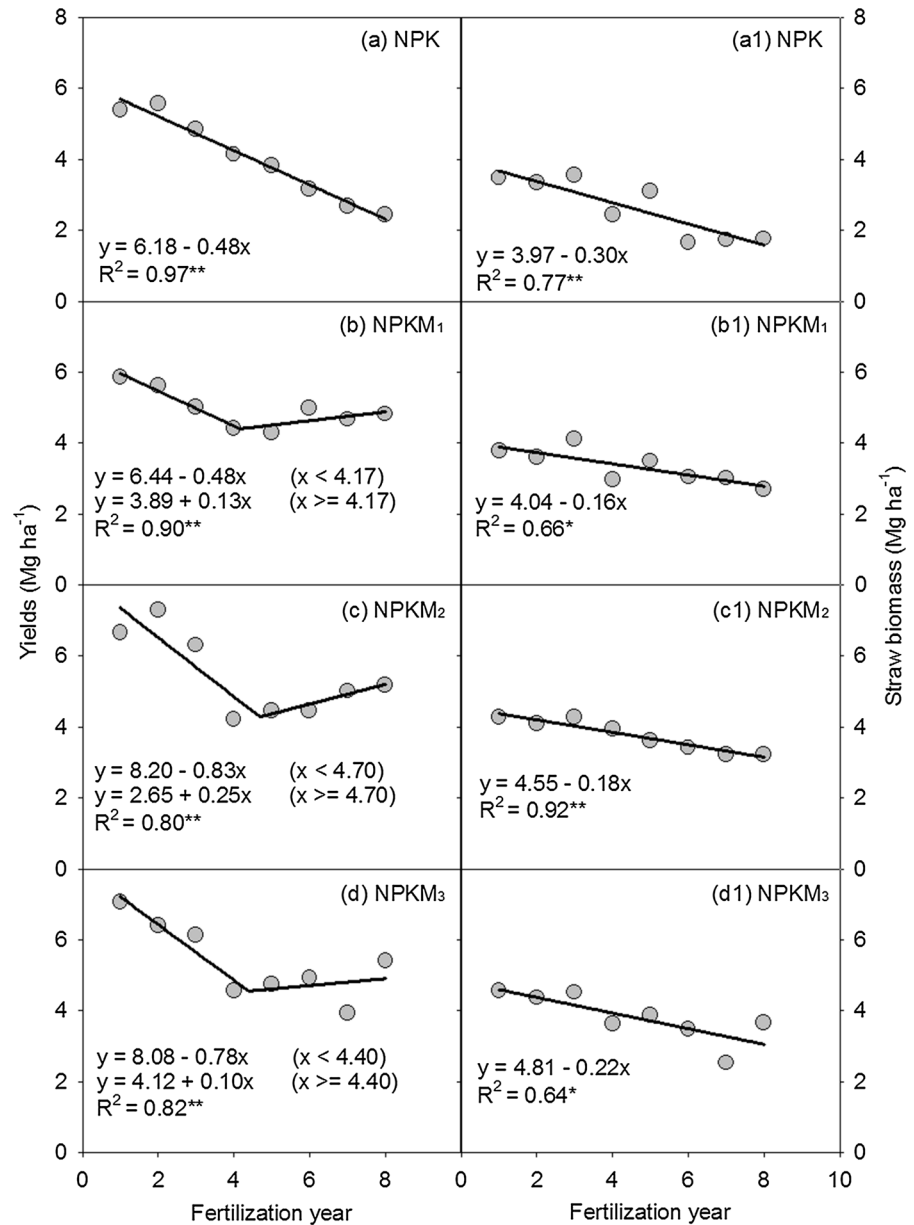
fertilizer combined with manure did not significantly increase the soil pH.

The nutrient balance sheet data showed that substantial N and P surpluses were present in all treatments (Table 3). There was more N surplus in the NPK treatment (156.0 kg ha^{-1} year^{-1}) than in the NPKM treatments (122.2–136.1 kg ha^{-1} year^{-1}). More P surplus was recorded in the NPKM treatments than in the NPK treatment (24 kg ha^{-1} year^{-1}), and the greatest P surplus occurred under NPKM$_3$

(122.6 kg ha^{-1} year^{-1}). In the NPK, NPKM$_1$, and NPKM$_2$ treatments, soil available K showed a deficit; however, in the NPKM$_3$ treatment, a slight increase in the K surplus was recorded (10.9 kg ha^{-1} year^{-1}).

Mechanisms of crop yield change

Based on the SEM, individual models were constructed to examine the direct and indirect effects of soil fertility (SOC, TN, available N, P, and K, and soil
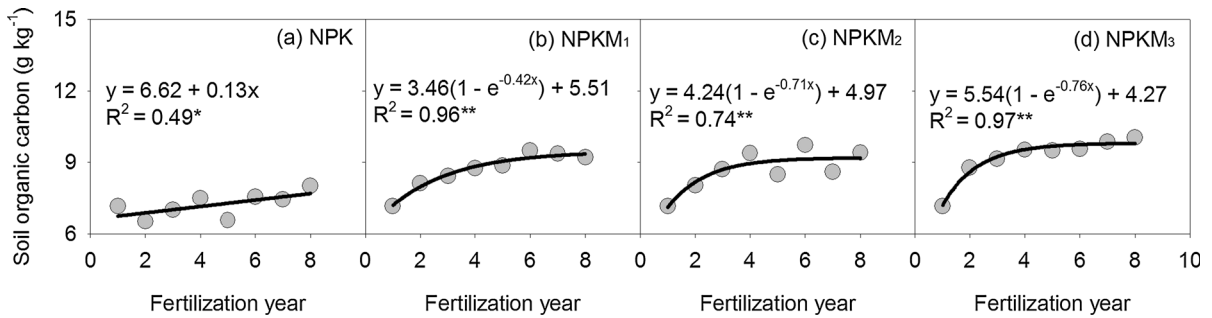
Fig. 2 Change in the SOC trend under various fertilization treatments during an 8-year period in a maize cropping system. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively
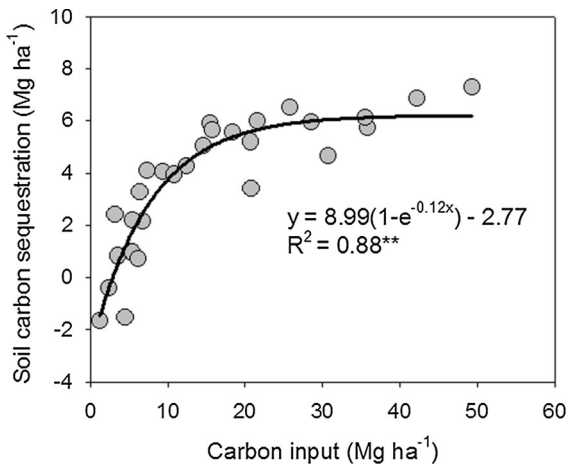

Fig. 3 Relationship between soil C sequestration and C input under all fertilization treatments during an 8-year period in a maize cropping system. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively

pH) on the variations in the crop yield. The path networks for the last four when regulating crop yield is displayed in Fig. 5. Applying manure mainly influenced the crop yield due to the indirect effects of the manure; these effects were associated with changes in the TN, available N, and available P. Manure strongly affected the available P and TN; these parameters had direct path coefficients of 0.86 and 0.54, respectively, indicating that manure positively affected crop yields via available P and TN. TN also indirectly influenced crop yield through the soil available N, which had a path coefficient of 0.79. Among the four regulating factors, available P was the most important for influencing the crop yield and had a direct path coefficient of 0.56. There is a direct link between the crop yield and manure, and the path coefficient of this link was 0.34. Combined manure fertilizers and soil

fertility (TN, available N, and available P) accounted for up to 64% of the variation in the crop yield.

Discussion

Soil fertility is the capacity of soil to provide physical, chemical and biological needs for the growth of plants for productivity. Manure application affects the crop yield by modifying soil quality, especially SOC and soil nutrients. The data showed that the differences in the crop yields among the treatments were due to the different nutrient levels (Table 2 and Figs. 2, 4). As expected, compared with chemical fertilizer, the combination of chemical fertilizer and manure induced a considerable increasing trend in maize yields, with 0.94–1.44 Mg ha^{-1}. These results are in accordance with previous studies (Shen et al. 2007; Fan et al. 2008). The yield responses were attributed mostly to the effects of the manure, which overcame macronutrient deficiencies and provided beneficial effects that enhanced the availability of micronutrients (Schoenau 2006). With respect to the nutrient application rates and nutrient balance sheet, no significant differences were observed between the treatments and N application rates. However, the results of the analysis showed that the manure applications performed best. Compared with the chemical fertilizers, the manure applications resulted in greater aboveground crop yields and straw biomass (89–102 kg ha^{-1} year^{-1}) (Tables 2, 3). These results occurred because the manure provided beneficial conditions and nutritive substances that are needed by plants the during the grain-filling period (Díez et al. 2010).
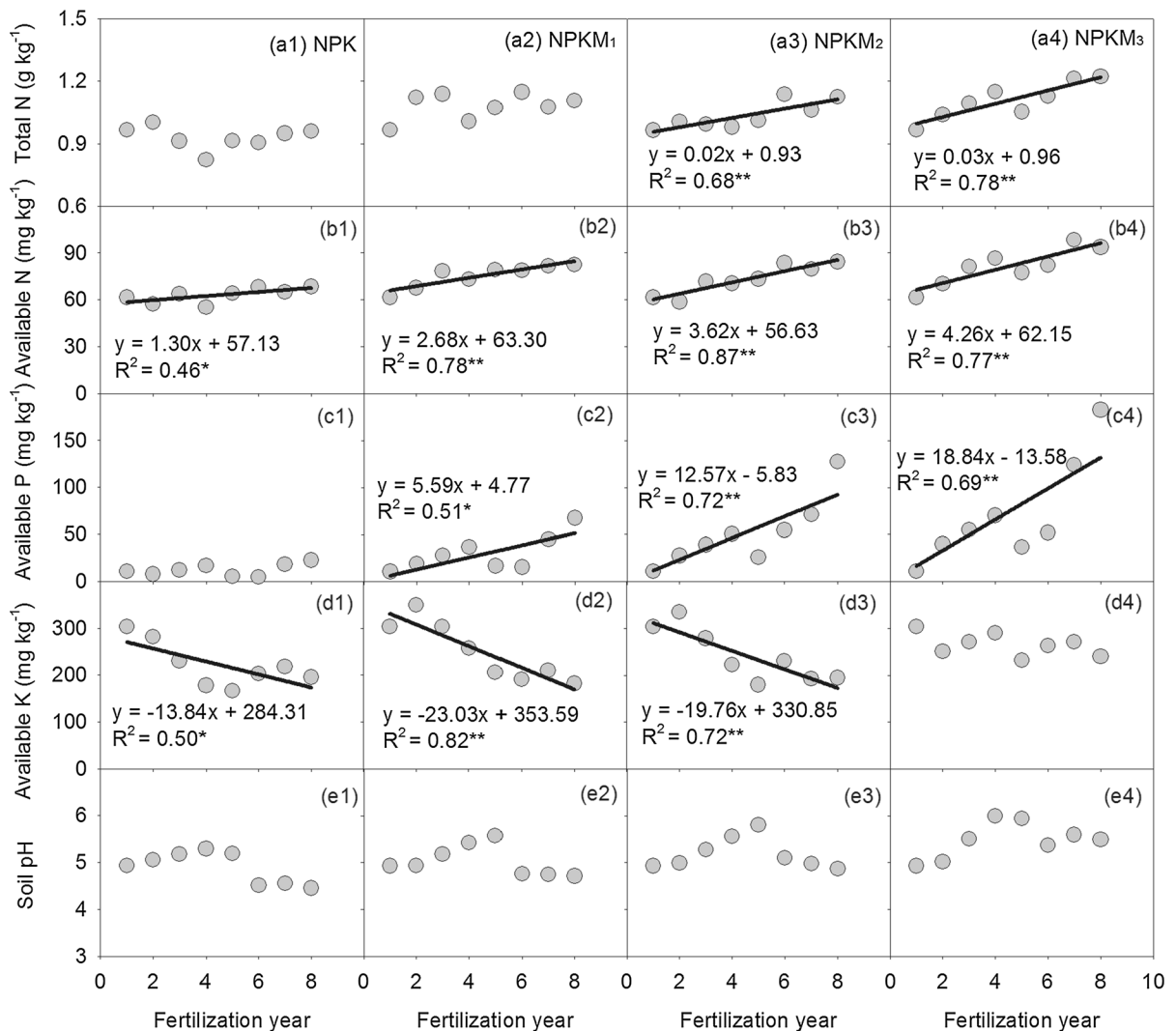
Fig. 4 Changes in the soil nutrient trends under various fertilization treatments during an 8-year period in a maize cropping system. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively

Table 3 Nutrient balance sheet containing data that were averaged over 8 years

Treatments	Total input (kg ha^{-1} year^{-1})			Aboveground biomass (kg ha^{-1} year^{-1})			Surplus/deficit (kg ha^{-1} year^{-1})		
	N	P	K	N	P	K	N	P	K
NPK	225	32.7	62.2	69.0	7.9	72.2	156.0	24.8	− 10.0
NPKM$_1$	225	68.7	84.7	88.9	10.6	102.1	136.1	58.2	− 17.4
NPKM$_2$	225	104.7	107.2	102.8	13.5	130.4	122.2	91.3	− 23.1
NPKM$_3$	225	140.7	129.7	98.3	18.1	118.8	126.7	122.6	10.9

The crop yield data showed a significant decreasing trend during the first 4 years, but an increasing trend during the subsequent 4 years under the combination of mineral fertilizer and manure treatments (Fig. 1).
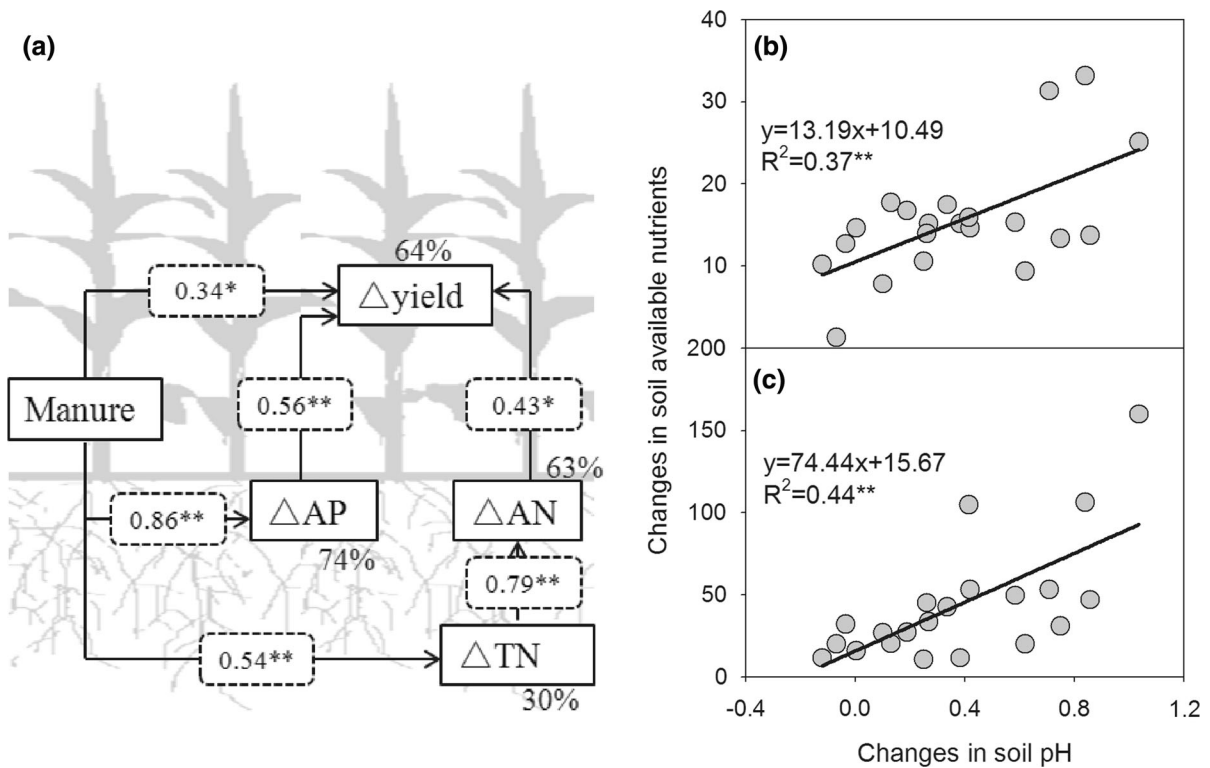
Fig. 5 Mechanisms underlying crop yield changes. The most parsimonious path model explains the underlying mechanisms of the positive relationship between manure, soil fertility, and crop yield change (**a**, chi/df = 1.47, P = 0.21; gfi = 0.91). Numbers next to the endogenous variables indicate their explained variance. Numbers next to the arrows indicate standardized path coefficients. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively. Relationships between both the soil pH and **b** soil available N and **c** soil available P changes are shown. *Notes* $\triangle$yield, crop yield change ($\triangle$yield = NPKM$_{yield}$ − NPK$_{yield}$, the same below); $\triangle$TN, soil TN change; $\triangle$AN, soil available N change; and $\triangle$AP, soil available P change

Similar results were reported for wheat yields by Zhang et al. (2009). These results are attributed to the direct and residual effects of manure on the yields (Silva et al. 2004; Shen et al. 2007). The available nutrients was released faster from the degradable components after manure incorporated into the soil (Silva et al. 2004). The residual effects of manure can maintain crop yield levels for several years after manure application ceases because only a fraction of the nutrients in manure are available to the plants in the early stages after application (Demelash et al. 2014). Therefore, the crop yield response to manure may extend beyond the year of application due to residual nutrient availability (Ramamurthy and Shivashankar 1996; Eghball et al. 2004). Positive residual effects of manure on maize yields have been reported; these effects can improve plant height and dry matter production at different stages of crop growth

(Ramamurthy and Shivashankar 1996). Our study is based on low soil fertility as well as low initial SOC (7.16 g kg^{-1}) and pH (4.93). Therefore, during the early stages, the application of manure mineralized some elements to slow down the decrease in crop yields under low-soil fertility conditions (Singh 2004; Judith et al. 2009). Long-term applications of manure and its residual effects therefore tend to cause crop yields to increase during the later stages.

Several investigations have demonstrated that SOC is a very reactive and ubiquitous soil quality indicator that influences the soil productivity (Lal 2004; Diacono and Montemurro 2010). In the present experiment, the SOC showed significant increasing trends under all the fertilizer treatments; these results corroborate those from similar subtropical areas in China (Pan et al. 2004; Zhang et al. 2012), indicating that the soil has served as a C sink during the past

decade. Non-linear regressions between the SOC and fertilization year under the manure treatments indicated that the SOC was approaching equilibrium. The SOC may have already reached equilibrium due to long-term manure applications in southern China (Li et al. 2010; Zhang et al. 2012). Our results also suggested that the exponential regression may explain the relationship between soil carbon sequestration and carbon input (Fig. 3); this finding is similar to those of other studies (Yan et al. 2013; Nicoloso et al. 2016). However, many researchers reported that the C sequestration efficiency is a fixed value and did not account for the rate of manure application (Kundu et al. 2007; Tong et al. 2014). The different relationships demonstrate the differences in C sequestration efficiency and C saturation limit (Stewart et al. 2007). The exponential relationship emphasizes the decrease in the C sequestration efficiency when the SOC approaches the equilibrium level (Stewart et al. 2007). Changing the C input will lead to a new balance in soil C sequestration and mineralization (Stewart et al. 2007). Therefore, the equilibrium level of SOC storage was found, as 6.22 Mg ha^{-1}.

A strong linear or non-linear relationship exists between crop production and SOC stocks (Lal 2010; Kong et al. 2014). However, the SEM results indicate that the influence of manure on crop yield does not occur via an SOC role in acidic soils (initial pH of 4.93), indicating that the SOC increase due to manure application occurred only to ensure soil fertility (Fig. 5a). Compared with the chemical fertilizer (NPK), the combination of mineral fertilizer and manure application (NPKM) increased the soil pH (Fig. 4). Manure applications can increase the soil pH but can also increase the soil salt as well as the exchangeable content (Santillán et al. 2014). This phenomenon is due to higher calcium and magnesium contents, which fix the acidifying ions and reduce the contents of those ions in the soil solution (Santillán et al. 2014). Soil acidification could result in N, P, K, calcium, magnesium, copper and zinc deficiencies for plant uptake, and thereby reduce crop yields (Wright 1989). Our results showed that significant linear relationships exist between soil pH changes and soil available N and P changes (Fig. 5b, c). Therefore, manure mainly influenced crop yields through its indirect effects associated with changes in the TN, available N, and available P under the different treatments (Fig. 5a). The quality of the manure largely

affects N and P mineralization, and might provide enough N and P sources for manure decomposition (Li et al. 2010). Additionally, manure application also increased the soil N and P contents, which provides beneficial conditions for crop growth. Manure may be directly related to crop yields. This relationship might be due to changes in the environmental conditions by manure application; in turn, these conditions can significantly alter bacterial communities and be conducive to crop growth (Xun et al. 2016).

Conclusions

Compared with the chemical treatment alone, the combination of chemical fertilizer and manure treatments resulted in higher and more stable yields. Positive residual effects of manure application on crop yields were recorded. The equilibrium level of SOC storage with C input was 6.22 Mg ha^{-1}. Manure application significantly increased soil available N and available P. According to the SEM, manure mainly influenced crop yield through its indirect effects associated with changes in TN, available N, and available P; these effects accounted for up to 64% of the variation in the crop yield. Overall, our results show that long-term manure fertilization can determine or improve the effects of soil fertility on crop yields in acidic soils in South China.

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