Long-term impact of fertilization on soil pH and fertility in an apple production system

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Abstract

We examined the effects of three fertilization treatments (CK, NPK, and NPKM) on soil pH, soil organic carbon (SOC), total nitrogen (TN), C/N ratio, and available nutrients [alkali extractable-N (AN), available phosphorus (AP), exchangeable K (EK)] in the plow layer (0–40 cm) in an apple orchard from 1988 to 2016 in North China, as well as the mechanisms of nitrogenous fertilizer action on soil acidification through a three-year experiment. The application of NPK and NPKM fertilizers improved SOC, TN, and available nutrients compared with the CK. The average C/N ratio decreased with the number of years of fertilization, and reached lowest in NPK treatment (6.80). By 2016, the soil pH in CK, NPK, and NPKM treatments was 6.17, 5.29, and 5.59, which were 0.16, 1.04 and 0.74, respectively, units lower than initial values. Compared with the previous 14 years (1988–2002), the latter 14 years (2002–2016) showed greater change rates of SOC, TN, C/N ratio, AN, AP, EK, and pH in all treatments. Further analysis showed that the highest net H^+ production rate was found in the N900 treatment ($136.8 \text{ kmol ha}^{-1} \text{ y}^{-1}$), followed by the N600 treatment ($88.6 \text{ kmol ha}^{-1} \text{ y}^{-1}$), and the lowest appeared in the N300 treatment ($50.6 \text{ kmol ha}^{-1} \text{ y}^{-1}$). Thus, long-term fertilization can remarkably increase SOC, TN, and available nutrients, especially in NPKM treatment; however, it also clearly decreased soil C/N ratio and pH due to the continuous excessive application of N fertilizers.

Keywords: Soil fertility, soil acidification, long-term fertilization, apple orchard soil

1. Introduction

To date, China has the largest apple cultivation area and production in the world. Its fruit production has gradually become an important pillar industry for increasing the income of farmers. However, there has been poor development of fertilizer recommendations with rapidly expanding production, with the result that farmers are applying large amounts of inorganic fertilizers to ensure high yields. From 2000 to 2007, the cultivation area of fruit trees in China increased by 17.2%, whereas the application of fertilizer grew by 209% (Li *et al.* 2010). At present, N utilization rate has reached 400 to 600 kg ha⁻¹ in apple orchards in China with an annually increasing trend (Hao *et al.* 2012). Excessive N fertilizer application might not only decrease the N utilization efficiency and the agricultural production benefits, but also lead to negative impact on soil quality and nitrate pollution in groundwater and surface waters (Ju *et al.*, 2006).

Fertilization can directly or indirectly change the physical, chemical, and microbial properties of the soil and, thus, alter soil productivity (Blair *et al.*, 2006; Suman *et al.*, 2009; Dong *et al.*, 2016; Serrano *et al.*, 2017). Long-term field experiments can be used to measure changes in soil quality under different fertilization management and predict fertilizer requirement for crops and soil-environment interactions. Over past decades, a great number of long-term experiments were initiated to examine the effects of fertilization on soil fertility in the world (Richter *et al.*, 2007). Some studies have documented that continuous fertilizer application increased the concentrations of soil organic carbon (SOC), total nitrogen (TN), and other nutrients in plow layers compared with no application and improve soil productivity (Huang *et al.*, 2010; Liu *et al.*, 2011; Velásquez *et al.*, 2016). However, other studies have shown that the continued use of fertilizers, especially N fertilizer, can accelerate soil acidification

and reduce base saturation, cation exchange capacity, soil aggregation, water-holding capacity, hydraulic conductivity, total porosity, resistance to water, and soil microbial activity, but increase soil bulk density and compaction, thereby decreasing soil productivity (Körschens, 2006; Leroy *et al.*, 2008). Thus, there's still some debate over the effect of different fertilization treatments on soil fertility because of the differences in soil types, crops, and climatic conditions. Although some long-term field experiments have been initiated in the brown soils in North China, a thorough understanding of how different fertilizers affect the long-term soil fertility under apple cropping systems is still lacking in Yantai city, one of the most important typical apple production regions in China. In this study, we measured SOC, STN, C/N ratio, and available nutrient concentrations in soils with 28 years' application of organic manure and inorganic fertilizer in Yantai City, Shandong province, north China. The present work aimed to: (i) assess the effects of fertilization on soil fertility and pH from 1988 to 2016, and (ii) investigate the mechanisms of N fertilization on soil acidification.

2. Materials and Methods

2.1. Experimental site

The experiment was conducted in Yantai city (120°34'10"~121°13'41" E, 37°05'34"~37°39'23" N) which was located in the warm temperate zone with a semi-humid continental monsoon climate and distinct seasons in North China. Over a 32-year period (1984-2016), the average temperature is 11.4 °C with 209 frost-free days each year, and the annual average precipitation is 778. The soil is classified as a Hapli-Udic Cambisol (FAO Classification), and

consisted of 16.7% sand, 58.4% silt and 24.9% clay at depth of 0–30 cm in 1984.

2.2. Experimental design

The experiment was conducted initially in 1988, the initial soil organic C and total N concentration of the plough layer (0–40 cm depth) were 4.34 and 0.45 g kg⁻¹; available N, P, and K concentration were 43.9, 18.1, and 35.8 mg kg⁻¹, respectively; soil pH (H₂O) was 6.33. There were three treatments in total: no fertilizer (CK), NPK (N, P, and K fertilizer); and NPKM (NPK fertilizer plus organic manure). Treatments were arranged in a randomized complete block design with three replications. The plots size was about 200 m² (12~13.5 m × 15~17.5 m), including three tree rows, totaling 15 apple trees. The detailed fertilization information is in Table 1.

The N, P, and K fertilizer were applied three times a year post harvest (about late November, 60% of the N, P, and K fertilizer), in late March (20% of the N, P, and K fertilizer) and in late June (20% of the N, P, and K fertilizer) in the NPK and NPKM treatments, and the organic manure was fertilized at post harvest (middle November). The inorganic fertilizers were urea, ammonium sulfate, ammonium nitrate, calcium magnesium phosphate, potassium chloride, and compound fertilizer (N-P₂O₅-K₂O=15-15-15). During 1988-2006, organic pig manure was used, which had a mean nutrient content of 237 g kg⁻¹ C, 24.3 g kg⁻¹ total N, 25.9 g kg⁻¹ total P, and 19.2 g kg⁻¹ total K. During 2006-2016, organic fertilizer was applied as commercial organic fertilizer, which contained 187 g kg⁻¹ C, 20.0 g kg⁻¹ total N, 15.0 g kg⁻¹ total P, and 15.0 g kg⁻¹ total K.

Table 1. The application rates of NPK fertilizer and organic manure in different fertilizer treatments during 1988-2016.

Time	Tree age (y)	CK (kg ha ⁻¹)	NPK (kg ha ⁻¹)			NPKM (kg ha ⁻¹)			Organic manure
			N	P	K	N	P	K	
1988-1990	1-3	0	100	80	100	100	80	100	8050
1991-1993	4-6	0	200	150	220	200	150	200	12700
1994-2004	7-17	0	450	200	380	450	200	450	9490
2005-2010	18-23	0	680	360	580	680	360	680	7490
2011-2016	23-28	0	860	450	800	860	450	860	6210

2.3. Soil sampling and analysis

Soil samples (0–40 cm depth) were collected in August 2002 and July 2016. In each plot, the soil was collected from twenty points randomly, and mixed into one sample. After carefully removing the surface organic materials and fine roots, each mixed soil sample was

air-dried for the analysis of soil chemical properties. Soil pH was determined in soil (air-dried) to water (w/w) ratio of 1:2.5 and measured with a pH meter. Soil organic carbon (SOC) was determined according to the Turin method, soil total nitrogen (TN) by Kjeldahl digestion–distillation method, soil alkali extractable-N (AN) by alkali hydrolysable method, soil available

phosphorus (AP) by Olsen method, and soil exchangeable potassium (EK) by Dirks-Sheffer method.

2.4. Soil acidification study

Soil acidification is the integrated result of a series of biogeochemical processes in the soil-plant system (Barak *et al.*, 1997). In agricultural ecosystems, crop

uptake of base cations (i.e., Na^+ , K^+ , Mg^{2+} , and Ca^{2+}) and anions (H_2PO_4^- and SO_4^{2-}) can be considered as the dominant source of acidity and alkalinity, respectively (Equation 1, 2, and 3) (Barak *et al.*, 1997; Guo *et al.*, 2010), assuming that the uptake and removal of these ions from soil leave an equivalent H^+ or OH^- in the soil:

$$\text{H}^+_{\text{BCs}} = \text{BCs}_f \times \text{Yield}_f + \text{BCs}_{\text{pl}} \times \text{Yield}_{\text{pl}} \quad \text{Equation 1}$$

$$\text{OH}^+_p = P_f \times \text{Yield}_f + P_{\text{pl}} \times \text{Yield}_{\text{pl}} \quad \text{Equation 2}$$

$$\text{OH}^-_s = S_f \times \text{Yield}_f + S_{\text{pl}} \times \text{Yield}_{\text{pl}} \quad \text{Equation 3}$$

where BCs_f , P_f , and S_f signify the dry weight-based concentration for base cations (BC), P, and S in fruit, respectively; and BCs_{pl} , P_{pl} , and S_{pl} denote the dry weight-based concentration for BC_s , P, and S in pruned branches and fallen leaves that were removed from the orchard. Yield_f and Yield_{pl} are the dry biomass values of fruit and pruned branches + fallen leaves, respectively.

N with both cationic (i.e., NH_4^+) and anionic (i.e., NO_3^-) forms exerts a somewhat complex contribution to soil acidification. Nitrification (from NH_4^+ to NO_3^-) and the uptake of NH_4^+ tend to acidify the soil, whereas the uptake of NO_3^- increases soil alkalinity. For N cycling, the contribution to soil acidification is calculated based on an ecosystem mass balance budget as in Equation 4 (Guo *et al.* 2010):

$$\text{H}^+ = (\text{NH}_4^+_{\text{In}} - \text{NH}_4^+_{\text{Out}}) + (\text{NO}_3^-_{\text{Out}} - \text{NO}_3^-_{\text{In}}) \quad \text{Equation 4}$$

Therefore, we studied these processes in a mature apple orchard in Sujadian town, Qixia City from 2012 to 2014. The apple orchard was dominated by 7-year-old ‘Fuji’ apple trees (*Malus domestica*/*Malus hupehensis*). The plant density was 680 plants ha^{-1} , and the plants were 3 × 5 m apart. The characteristics of the soil at the depth of 0–40 cm are: organic matter 12.0 g kg^{-1} , AN 89.4 mg kg^{-1} , AP 37.7 mg kg^{-1} , EK 126.4

mg kg^{-1} , and pH (H_2O) 5.42. The soil bulk density of the 0–20 and 20–40 cm layers were 1.13 and 1.28 g cm^{-3} , respectively. Twelve plots were randomly selected in the apple orchard, each covering 96 m^2 with eight apple plants. Every three plots were a repetition. The N application treatments were 0 kg N ha^{-1} (N0), 300 kg N ha^{-1} (N300), 600 kg N ha^{-1} (N600), and 900 kg N ha^{-1} (farmers’ customary dosage, N900).

The N fertilizer was urea (46% N), the phosphate (P) fertilizer was superphosphate (P_2O_5 400 kg ha⁻¹), and the potassium (K) fertilizer was potassium sulfate (K_2O 400 kg ha⁻¹). The N, P, and K fertilizer was applied in two split applications at a soil depth of ~15 cm by digging a fertilization band (15 cm depth, 30 cm width) at 1.5 m from tree row in late November (60% of the N, P, and K fertilizer), late March (20% of the N, P, and K fertilizer) and late June (20% of the N, P, and K fertilizer). NH_4^+ in is the input of NH_4^+ from the atmospheric deposition, irrigation, and chemical N fertilizer.

NH_4^+ in added by atmospheric nitrogen deposition and irrigation is 19.9 kg N ha⁻¹ yr⁻¹ (Guo *et al.*, 2010). According to the nationwide situation in China, 90% of chemical N fertilizers were assumed as NH_4^+ (Zhu and Chen, 2002). NH_4^+ out is assumed to be zero because NH_4^+ leaching is negligible in Chinese agricultural systems (Zhu and Chen, 2002). NO_3^- in added by atmospheric nitrogen deposition and irrigation is 21.10 kg N ha⁻¹ yr⁻¹ (Guo *et al.*, 2010). NO_3^- out is the efflux of NO_3^- from the topsoil (0–40 cm in apple orchard in this area) and mainly includes NO_3^- leaching in deeper soil layers (> 40 cm) and runoff. Because NO_3^- out is difficult to directly measure, it was estimated as the difference between N inputs and outputs: NO_3^- out = total N inputs – (tree remove + NH_3 volatilization + NO_2 emission + N residual in topsoil). Fruit thinning was carried out manually in May in each year, and the number of fruits and total fresh weight (FW) removed from each tree were recorded, and a subsample of the thinning-fruits was sampled for total N content analysis. At the end of October in each year, apple fruits were harvested, we also recorded the FW in each tree in the three N application treatments, and sampled and analyzed the total N content. Winter pruning was carried out in December–January, the branches mass removed per tree was recorded, and a subsample was taken, dried, and stored for total N content analysis.

N residual in topsoil = total soil N at the end of the experiment total soil N at the beginning of the experiment. Soil sampling was done under the canopy (about 60 cm inside the dripline of the canopy) of every tree in the three N application treatments plots at 0–20 and 20–40 cm depths. At each depth, twelve core (5.0 cm diameter) samples were taken, and pooled as a single sample per plot. Then, total N concentration in soil samples was determined through Kjeldahl analysis. Ammonia volatilizations and nitrous oxide emissions were calculated as 5.76% and 2.31% of the nitrogen input according to Ge *et al.* (2010, 2015).

3. Results

3.1. SOC, TN, C/N ratio, and available nutrients

Soil organic C and total N concentrations changed positively across the fertilization treatments and years (Figure 1). We observed that the application of fertilizers (NPK, and NPKM fertilizers) significantly increased SOC and TN concentration compared with the CK in 2002 and 2016. Specifically, the NPKM treatment resulted in the highest SOC and TN concentrations (6.47 and 0.71 g kg⁻¹ in 2002, 9.17 and 1.22 g kg⁻¹ in 2016), which were 11.9%, 4.41% and 20.3%, 8.93% higher than that of NPK treatment in 2002 and 2016, respectively. The order of SOC and TN change rates in the three fertilization treatments was NPKM > NPK > CK.

Although SOC and TN concentration increased in all treatments, soil C/N ratio decreased compared to control (Figure 1). By 2002, there were no significant differences of soil C/N ratios in CK, and NPKM treatment, but both the two treatments were significantly higher than that of NPK treatment. Soil C/N ratio decreased from 2002 to 2016, and the values in CK, NPK, and NPKM treatments were 9.27, 6.80 and 7.52, respectively. By 2016, soil C/N ratio in CK was 36.3% and 23.3% higher than that of NPK, and NPKM treatments, respectively.

Figure 1. SOC, TN, and C/N ratio in the different fertilizer treatments in the three investigated time periods. CK: no fertilizer; NPK: N, P, and K fertilizer; NPKM: N, P, and K fertilizer and organic manure.

After 14 and 28 years of fertilization, AN, AP, and EK significantly increased in NPK and NPKM treatments compared to the control and increased with years (Figure 2). In the CK treatment, AN, AP, and EK decreased due to uptake by the apple trees. During the experiment period, the AN, AP, and EK concentration in NPKM were significantly higher than that of NPK treatment.

Figure 2. Average soil AN, AP, and EK in the different fertilizer treatments in the three investigated time periods. CK: no fertilizer; NPK: N, P, and K fertilizer; NPKM: N, P, and K fertilizer and organic manure.

3.2. Soil pH

In 1988, the average soil pH of the apple orchards was 6.33. By 2002, the soil was clearly acidified, and the soil pH decreased from original value of 6.33 in the control to 6.26, 5.90, and 6.03 in CK, NPK, and NPKM, respectively. By 2016, the soil pH in NPK and

NPKM were 5.29 and 5.59, respectively, which were 0.88 and 0.58 units lower than that of CK (Figure 3). After 28 years, the soil pH in CK, NPK, and NPKM treatments were 0.16, 1.04, and 0.74 units lower than the initial value in 1988.

Figure 3. Average soil pH in the different fertilizer treatment in the three investigated time periods. CK: no fertilizer; NPK: N, P, and K fertilizer; NPKM: N, P, and K fertilizer and organic manure.

3.3. H^+ production budget

With an increase in N application rate, dry biomass of fruits slightly increased, but dry biomass of pruned

branches and fallen leaves sharply increased. Therefore, the highest H^+ production rate by BC uptake and OH^- production rate by P and S uptake were found in N900 treatment, which was significantly higher than that of N300 and N600 treatments, respectively (Table 2).

As shown in Table 3, N input includes atmospheric nitrogen deposition, irrigation, and N fertilizer. With an increase in N application rate, NO_3^- out sharply increased. Calculations based on inputs and outputs of NH_4^+-N and NO_3^--N indicate that N loading contributes 31.1, 65.4, and 103.6 $kmol\ ha^{-1}\ yr^{-1}$ of proton generation in N300, N600, and N900, respectively. Considering the four biochemical processes (N cycling, uptake of BCs, P, and S), the net H^+ production was calculated in the three N fertilization treatments (Figure 4). The highest net H^+ production rate was found in the N900 treatment, reaching 136.8 $kmol\ ha^{-1}\ yr^{-1}$, followed by the N600 treatment at 88.6 $kmol\ ha^{-1}\ yr^{-1}$ and the lowest appeared in the N300 treatment (50.6 $kmol\ ha^{-1}\ yr^{-1}$). In the N300 treatment, H^+ production caused by N application was 1.30 times that of uptake of BCs, but the value was 2.22 and 2.51 in N600 and N900 treatments, respectively.

Table 2. Annual uptake and H^+/OH^- production of base cations (BCs), phosphorus, and sulfur in the three N application rate treatments.

	Dry biomass $t\ ha^{-1}\ yr^{-1}$		BCs uptake $kmol\ ha^{-1}\ yr^{-1}$		H^+ Production	P uptake $kmol\ ha^{-1}\ yr^{-1}$		OH^- Production	S uptake $kmol\ ha^{-1}\ yr^{-1}$		OH^- Production
	Fruit	P+FL	Fruit	P+FL		Fruit	P+FL		Fruit	P+FL	
N300	30.4	10.5	10.2	13.7	24.0 c	0.82	0.36	1.18 c	2.34	0.96	3.30 c
N600	32.2	18.7	12.1	17.4	29.5 b	0.96	0.65	1.61 b	2.78	1.94	4.72 b
N900	35.2	29.5	14.6	26.7	41.4 a	1.14	0.92	2.06 a	3.53	2.65	6.18 a

The value was the average of three years (2012, 2013, and 2014). P+FL denote pruned branches and fallen leaves. All data was the mean of result of three years (2012, 2013, and 2014). Letters (a, b) indicate significant differences in the row at the 1% level.

Table 3. Nitrogen budgets and H⁺ production rate in the three N application rate treatments

	Inputs (kg N ha ⁻¹ y ⁻¹)			Outputs (kg N ha ⁻¹ y ⁻¹)					H ⁺ production kmol ha ⁻¹ y ⁻¹
	Deposition + irrigation		N fertilization	Plant uptake	NH ₃ volatilization	N ₂ O emission	Residue (0-40 cm)	Leaching + runoff	
	NH ₄ ⁺ - N	NO ₃ ⁻ - N							
N300	19.9	21.1	300	76.1	17.3	6.93	33.4	166.2	31.1 c
N600	19.9	21.1	600	124.9	34.6	13.9	61.5	365.2	65.4 b
N900	19.9	21.1	900	137.9	51.8	20.8	65.2	624.3	103.7 a

The data in the three N treatments in item of N fate was equal to the determined value subtract the basic value in N0. All data was the mean of result of three years (2012, 2013, and 2014). Letters (a, b) indicate significant differences in the row at the 1% level.

Figure 4. H⁺ production budget of apple orchards systems. Net H production is the algebraic sum of H resulting from N cycling as well as P, S, and BCs uptake. Data denote the means $\pm$ SD.

4. Discussion

Numerous studies have indicated that the long-term application of organic or inorganic fertilizers can increase the content of SOC and TN, with these increases enhanced by organic fertilizers (Hati *et al.*, 2008; Dong *et al.*, 2012). In our experiments, SOC and TN concentration increased considerably in the fertilization treatments compared with CK, especially in NPKM treatments, suggesting that organic and chemical fertilizer are beneficial to the accumulation of soil organic matter, thereby improving soil fertility.

We also found that the rate of change of SOC and TN in the latter 14 years (2002-2016) was much higher than that of the previous 14 years (1988-2012), which most likely resulted from the significantly higher fertilizer application rate in the latter 14 years than the previous 14 years. N fertilizer may increase SOC and TN content in two ways: directly, by the immobilization of fertilizer N; and indirectly, by increasing inputs of organic N in the form of tree roots and residues. N fertilizer may increase both the amount of crop residue and the N concentration; the latter would likewise influence its rate of mineralization (Chen *et al.*, 2010). Previous studies have pointed out that the soil C/N ratio plays a key role in the mineralization and accumulation of SOC and TN concentration, with high C/N ratio fostering high SOC and TN accumulation and low C/N ratio exhibiting lower accumulation due to increased C and N mineralization (Khalil *et al.*, 2005). Many long-term field experiments manifested that a long-term application of organic or inorganic fertilizers can increase soil C/N ratio as compared with no fertilizer application, and the C/N ratio was higher in OM applications than the other treatments due to the fact that C was added in addition to N in this treatment (Blair *et al.*, 2006; Dong *et al.*, 2012). In our experiment, with the prolonged fertilizing time,

the content of SOC and TN significantly increased, but the soil C/N ratio decreased. There may be two reasons for this pattern: 1) the continuous application of high rate of N fertilization led to increased accumulation of N compared to C in the soil; and/or 2) C and N were added through manure and greater C/N ratio in NPKM compared to NPK probably increased C and N inputs from manure with concomitant slower mineralization of C compared to N in the NPKM treatment (Khalil *et al.*, 2005).

Fertilization is crucial for maintaining soil available nutrient levels, because fertilization ensures the largely constant presence of active microorganisms and the regular dynamic of biomass carbon (Nardi *et al.*, 2004). Our research also showed that soil available nutrient (AN, AP, and EK) concentration were significantly affected by different fertilization treatments. Long-term NPK and NPKM application led to significantly higher values of soil AN, AP, and EK compared to the control, and the highest values were found in the NPKM treatment. These results suggested that the long-term application of organic matter played a major role in releasing soil AN and maintaining soil P and K availability. In addition, application of organic matter can improve soil microbial activity, soil aggregation, and soil cation exchange capacity, which is much more conducive to decrease soil nutrient leaching losses (Huang *et al.*, 2010). Although fertilization significantly increased the soil available nutrient concentrations, continuous high fertilizer input may bring about many negative impacts, such as: 1) excess nutrients entering into the deep soil along with rain or irrigation and, thus, influencing the safety of groundwater (Ju *et al.*, 2006); and 2) the higher AK content in soil may affect the absorption of calcium and lead to calcium deficiency and bitter pit, which frequently occurs in this apple production area (Milošević and Milošević, 2015). Some studies demonstrated that the soil pH was decreased to a certain extent with different fertilizer

treatments, and the annual decline rate was from 0.01 to 0.07 units (Daugelene and Butkute, 2008; Zhang *et al.*, 2009). In our study, the soil pH tended to drop in fertilization treatments with time, and the highest decline rate appeared in NPK treatment, and then in the NPKM treatment. We also found that the soil pH decline rate in the latter 14 years (2002-2016) was much higher than that of the previous 14 years (1988-2002) whether in NPK or in NPKM treatment, this may be due to the different application rate of N fertilizers. Through the three-year experiment from 2012 to 2014, further analysis shows that the recent soil acidification in China's apple orchards resulted mainly from high-N fertilizer inputs. In the study, calculations based on N cycling indicate that N loading contributes 31.1~103.7 kmol H⁺ ha⁻¹ y⁻¹ of H⁺ generation in these systems, and the value increased with the increase of N application rate. In the farmers' customary N application dosage (900 kg N ha⁻¹), the H⁺ generation related to N cycling (103.7 kmol H⁺ ha⁻¹ y⁻¹) in the apple orchards was extremely high compared with values (1.41 to 11.5 kmol H⁺ ha⁻¹ y⁻¹) at lower N fertilizer rates in other regions (Fujii *et al.*, 2009) and values (20.2 to 32.8 kmol H⁺ ha⁻¹ y⁻¹) at three Chinese double-cropping cereal systems (wheat-maize, rice-wheat, and rice-rice; N fertilizer rates above 500 kg N ha⁻¹ y⁻¹ with N use efficiencies of only 30% to 50%) (Guo *et al.*, 2010). However, this is rather low compared with China's greenhouse vegetable systems (220 kmol H⁺ ha⁻¹ y⁻¹, N fertilizer rates above 4000 kg N ha⁻¹ y⁻¹ with N use efficiencies below 10%) (Guo *et al.*, 2010). Plant uptake of BCs together with the removal of economic yields and crop residues from fields is another driver of soil acidification, because the net removal of excess cations over anions leaves behind an equivalent H⁺ released to the soil. Increasing N fertilizer applications have been a major management technique thought to drive high fruit yield. In fact, when the nitrogen application rate reached a certain level,

the increase of N application rate had no significant effect on fruit yield in mature orchard (Ernani and Dias, 1999; Li *et al.*, 2002; Xi *et al.*, 2010), which in turn increases the removal of BCs. At the current fertilization levels ($\sim 900 \text{ kg N ha}^{-1}$), approximately 64.8 tons of dry biomass (fruit, pruned branches, and fallen leaves) are harvested annually in the apple systems, leading to an estimated H^+ production rate by the BCs uptake of $41.4 \text{ kmol ha}^{-1} \text{ y}^{-1}$. Although acid deposition is an important environmental problem in China, strongly affected areas with a precipitation pH of 4.0–5.6 receive $0.4\text{--}2.0 \text{ kmol H}^+ \text{ ha}^{-1} \text{ y}^{-1}$, much of this is buffered by other depositional or soil processes (Wu *et al.*, 2006). Overall, soil acidification driven by N fertilization is at least 30–150 times greater than that associated with acid deposition.

5. Conclusions

Significant differences were observed in the soil quality of apple orchards under long-term different fertilization system in North China Plain. Application of NPK and NPKM resulted in a substantial increase of SOC, TN, AN, AP, and EK, especially in NPKM treatment. However, soil C/N ratio and pH clearly decreased, especially in NPK treatment. Further studies demonstrate that the major factor causing the soil acidification in this area was the continuous excessive application of N fertilizers. Thus, organic manure should be recommended to improve soil quality in apple orchards in this region. Moreover, the fertilization system of apple orchards should change from the conventional system to the optimal nutrient-management system as soon as possible, and use the methods of soil nutrient testing and leaf diagnosis to reduce the amount of inorganic fertilizer. This should be achieved by long-term studies to determine more accurately apple N requirements and by enhancing the local extension service to persuade farmers to re-

duce fertilizer application rate while maintaining high crop yields.

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