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Physicochemical Properties of a Red Soil Affected by the Long-term Application of Organic and Inorganic Fertilizers

Yanling Wang and Hailin Zhang

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Abstract

Red soils are widespread throughout subtropical and tropical regions and are the most important resources for grain production in South China. Application of chemical fertilizers alone or chemical fertilizers combined with organic amendments is commonly practiced to improve physicochemical properties and fertility for red soils. This chapter summarizes the findings of a 22-year long-term field experiment conducted in the red soil region of south central China. Changes in soil pH, soil organic matter (OM), nitrogen (N), phosphorus (P), and aggregate distribution and stability as affected by the long-term fertilization treatments were examined and discussed. Combined application of chemical fertilizer and rice straw or pig manure significantly increased soil pH in the first 7 years, but soil pH decreased linearly at a rate of 0.04–0.07 unit yearly since then. Soil total N and total P content significantly increased during the long-term fertilization, and the effects of pig manure addition on N and P build-up were greater than that of rice straw addition. In contrast, soil total potassium (K) contents significantly decreased by the long-term fertilization. There was a significant difference between the effect of rice straw addition and pig manure amendment on various aggregate size distribution in the red soil.

Keywords: red soil, soil physicochemical properties, rice straw, pig manure, aggregate structure

1. Introduction

Red soil, which is widespread throughout subtropical and tropical regions, is the most important grain production base in South China. Red soils are naturally poor in physical conditions and

are also characterized by low pH, cation exchange capacity (CEC), and fertility. Red soil also has low concentrations of P in soil solution and results in frequent P deficiency of plants [1]. The improvements of soil fertility especially plant available P level, soil pH, soil structure, and water-holding capacity in the red soil region are always a major challenge. The application of chemical fertilizer alone, and that combined with organic fertilizers, such as crop residues and farm-yard manure, are two common approaches to improving soil quality for grain production [2–5]. Rice (*Oryza sativa* L.) is the main cereal crop in the red soil region. Returning rice straw containing C, N, P, K and microelements to the soil (both used as a surface cover and incorporated) has been extensively shown to increase organic matter and nutrient contents resulting in improved soil physical, chemical and biological characteristics. Crop residue is returning not only can increase crop yields, but it also can enhance soils' resistance to wind and water erosion [6, 7]. Animal manures, such as pig manure with ample N, P and K, are valuable resources to supply the needed plant nutrients and organic matters [2, 4, 5, 8, 9].

Therefore, rice straw and fresh pig manure are commonly used as organic amendments in the red soil region of China. When combined with chemical fertilizers, those organic amendments could effectively regulate soil physicochemical properties and soil fertility. Many researchers have proven that long-term application of organic-inorganic fertilizers significantly increased soil water supply capacity, promoted soil nutrient recycle and distribution, improved soil aggregate structure [2]. Therefore, in this chapter, the changes or fluctuations of soil acidity, soil organic matter, soil NPK fertility, and soil aggregate structure due to the combined application of chemical fertilizer and rice straw or pig manure in a long-term (1988–2009) experiment were summarized. Lessons learned can be used to improve nutrient management so that crop yields are optimized and the impact of food production on the environment is minimized.

2. The nature and properties of red soils

2.1. Distribution of red soils in southern China

Red soils are mainly distributed in the tropical and subtropical zone all over the world, which occupy around 6.4×10^9 ha, accounting to about 45% of the world land area. In addition, most of the red soils are distributed in the developing countries. The population living in the red soil regions is about 2.5 billion, roughly 48% of the global population [10]. Various types of yellow or red soils collectively known as red soil series, such as laterite, laterite red soil, red soil, and yellow soil (equivalent to ferrisol or ultisol [11]), are widespread in southern China. Scattered patches of similar soil are also seen in south central China. The total area of red soil in China is about 2.18×10^8 ha, covering about 21.8% of the total land area, or 28% of the farmland area. However, the population in the red soil series region accounts for 40% of the overall national population [10, 12] due to its warm and humid climate.

2.2. Basic properties of red soils

Rich in iron-aluminum (hydr)oxides with strong fixation capacity of phosphate, low pH, and organic matter content, and poor nutrient availability are the main yield-limiting factors for the red soils. According to the results of the second national soil census data, the fertility of major red soils was moderate or poor (**Tables 1 and 2**). Soil phosphorus (P) availability of red soils was considered seriously deficient. These serious P-deficient red soils cover most of the farmland in the region. Soil potassium (K) of the red soils is not as bad as P by 26.3 and 13.6% of the red soil area considered moderate and seriously deficient, respectively. Soil nitrogen (N) status of the red soils is situated between the P and the K with most in the moderate and serious deficient category [12, 13].

Soil type	Nutrition level (Code)	Organic matter	Total N	Total P	Total K	Available P	Available K
		g kg⁻¹				mg kg⁻¹	
Natural soil	Fertile (A)	>35	>1.75	>1.0	>30	>10	>150
	Mild deficiency (B)	25–35	1.25–1.75	0.6–1.0	20–30	5–10	100–150
	Moderate deficiency (C)	15–15	0.75–1.25	0.2–0.6	10–20	2.5–5	50–100
	Severe deficiency (D)	<15	<0.75	<0.2	<10	<2.5	<50
Upland soil	Fertile (A)	>20	>1.5	>1.0	>30	>10	>150
	Mild deficiency (B)	15–20	1.0–1.5	0.6–1.0	20–30	8–10	100–150
	Moderate deficiency (C)	10–15	0.5–1.0	0.2–0.6	10–20	5–8	50–100
	Severe deficiency (D)	<10	<0.5	<0.2	<10	<5	<50

Table 1. Evaluation standard of soil fertility status of the hilly upland red soil in southern China [12].

Province (District)	Organic matter	Total N	Total P	Total K	Available P	Available K
	g kg⁻¹				mg kg⁻¹	
Hunan	20.6 (A*)	1.14 (B)	1.03 (B)	20.0 (B)	8.2 (B)	98.7 (C)
Jiangxi	20.9 (A)	1.03 (B)	0.55 (C)	12.4 (C)	17.6 (A)	91.0 (C)
Zhejiang	19.8 (B)	1.06 (B)	0.56 (C)	11.1 (C)	6.9 (C)	105.5 (B)

* Capital letter in the bracket represents soil with different fertility level. A, fertile; B, mild deficiency; C, moderate deficiency; D, severe deficiency.

Table 2. Average content of various soil nutrients and their corresponding soil fertility level in the upland red soils from Hunan, Jiangxi, and Zhejiang provinces, China [12].

3. Long-term application of fertilizers

3.1. Commonly used organic fertilizers in the red soil region

Commonly used organic fertilizers in the red soil region come mainly from green manure, farmyard manure, and crop residues (returned and left in place). In this area, rice and rapeseed are the main field crops covering 55 and 11% of the total cropped area, respectively. The amount of rice straw and rapeseed stalk account for 70–75% and 8.5–11% of the total crop residues in this region [14]. Double rice (two rice crops per year) and winter rapeseed is the main cropping pattern producing 9500–1200 kg hm² straw yearly, but the rapeseed only yield about 1660–6900 kg hm² residue yearly. Dry land crop straw is mainly used as livestock feed and cooking fuel, and only small portion is returned to the field. Radish (*Raphanus sativus*) and milk vetch (*Astragalus sinicus* L.) are also used as the main winter green manure which produced about 10,500–15,000 kg hm² fresh biomass yearly. Pig and cattle manure were the main livestock manures in the region [14]. Crop, especially rice, above and below ground residue is another important source of soil organic matter. The nutrient contents of major organic materials used in the typical red soil region, Yujiang Country, Jiangxi Province, China, are presented in **Table 3**

Type	C	Total N	C/N ratio	Total P	Total potassium
	g kg ⁻¹			g kg ⁻¹	
Cattle dung	404.1	18.82	21.5	7.19	4.37
Pig dung	368.4	24.36	15.1	9.36	2.80
Milk vetch	440.2	30.82	14.3	3.65	26.02
Radish	429.6	23.41	18.4	2.82	18.12
Peanut straw	435.6	12.48	34.9	0.84	12.61
Cole stalk	467.4	5.22	89.7	0.46	15.72
Rice straw	432.4	10.89	39.7	0.55	19.95
Wheat straw	457.5	6.12	74.8	0.66	7.90
Rice root	306.2	8.38	36.5	1.23	3.57
Wheat root	329.6	6.34	52.1	0.89	4.05

Table 3. Nutrient contents of major organic materials used at the Yujiang Country, Jiangxi Province, a typical red soil region [14].

3.2. Long-term fertilization experiment on a typical red soil

The Red Soil Ecological Experiment Station, constructed in 1985 by the Institute of Soil Science, Chinese Academy of Sciences (ISSAS), is located in Liujia Zhan, Yujiang County, Jiangxi Province, China (28°15′20″ N, 116°55′30″ E). It is one of the key laboratories for studying the ecology of red soils in China. Red Soil Ecological Experiment Station is dedicated to finding

solutions to ecologically sound and environmentally friendly use of the red soil resources. It primarily explores (1) the structure, function, and productivity of red soil agricultural ecosystems; (2) the characteristics of material cycling and energy transformation between red soils and the environment; and (3) the relationships among regional resources, the environment, and the economy, in order to provide a scientific basis for sustainable development of the region.

In order to understand the changes of soil physicochemical properties, soil fertility, and the sustainable utilization of red soil as affected by the combined application of organic–inorganic fertilizers and the response of the cultivated crops to those changes and variations, a long-term fertilization experiment was established at the station in 1988. The experiment had a completely randomized block design with five fertilizer treatments and three replications. Each plot was 33.3 m². In this chapter, three relevant treatments were chosen for discussion. Those treatments were: NPK (control, CK), CK plus rice (*Oryza sativa* L.) straw (RS) and CK plus pig manure (PM). The crops grown during the experiment before 1995 included peanut (*Arachis hypogaea* L.) in Season 1 (April–August) and cole (*Brassica napus* L. var. *napus*) in Season 2 (September–December). Since 1995, peanut was planted in Season 1 and the land was followed in Season 2. The sources of chemical fertilizers for the experiment were urea for N, KCl for K, and Ca-Mg phosphate for P. The amounts of chemical fertilizers applied to the plots every year were as follows: N, 60.0 kg hm⁻²; P₂O₅, 19.65 kg hm⁻²; K, 58.85 kg hm⁻². At the same time, 3000 kg hm⁻² of rice straw (dry weight) and 30,000 kg hm⁻² of fresh pig manure were added to the Treatment RS and PM in addition to chemical fertilizers, respectively. Nutrient contents of the rice straw and pig manure on dry weight basis were as follows: organic carbon, 376.0 and 265 g kg⁻¹; total N, 6.7 and 36.5 g kg⁻¹; total P, 2.0 and 23.0 g kg⁻¹; Total K, 23.0 and 52.0 g kg⁻¹; C/N ratio, 56.1 and 7.26, respectively.

The test site is in the typical middle subtropical region, with a mean annual rainfall of 1785 mm (ranging 1040–2550 mm) during the past 22 years, a mean annual temperature of 17.8°C (ranging 16.1–18.9°C), and the frost-free days per year ranged from 240 to 300 days. The soil at the site is a typical udic ferrosol [11] with kaolinite red clay parent material of Quaternary age. Before the long-term experiment, the land was a gently sloping hill covered with herbaceous vegetation with no history of crop production, and partial chemical and physical characteristics of the soils tested in 1988 were as follows: pH, 4.65; soil organic carbon, 3.71 g kg⁻¹; TN, 0.34 g kg⁻¹; TP 0.53 g kg⁻¹; 10.6 g kg⁻¹; C/N ratio, 10.9.

4. The effects of organic-chemical fertilizer application on soil properties

4.1. Soil acidity

Soil pH had a significant increasing trend during the long-term organic–inorganic fertilization (**Figure 1**) from 1988 to 1995, but it gradually decreased since then. There was a significant negative linear correlation between soil pH and cultivation time after the seventh year of the experiment. This suggests that initial fertilization raised pH in the very acidic soil to near neutral, but continuous fertilization led to further soil acidification. The mechanism of pH

changes remains to be explored. The CK treatment decreased soil pH by 0.07 yearly, while addition of rice straw and pig manure decreased the pH by 0.05 and 0.04 yearly, respectively (**Figure 1**). At the rate of pH decline, soil acidity of the upland red soil would reach the original soil condition in 1988 after 30 (CK and RS) or 48 (PM) years of cultivation. In addition, soil pH of RS treatment decreased faster than that of the PM treatment after the seventh year.

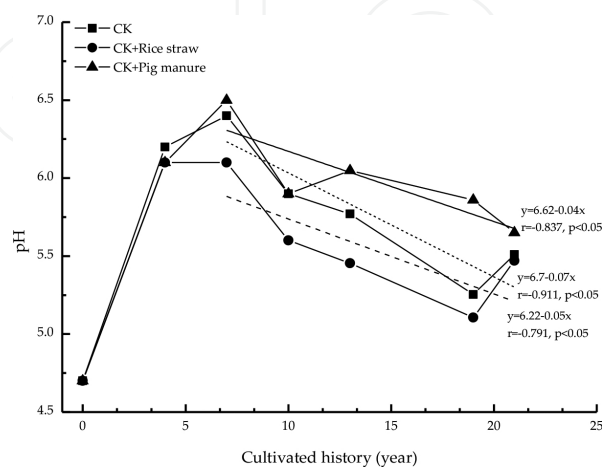


Figure 1. Changes of soil pH in the upland red soil as affected by the long-term application of organic–inorganic fertilizers (1988–2009).

4.2. Soil organic matter

Compared with the CK, addition of rice straw and pig manure significantly increased soil organic matter contents in the upland red soil during the long-term fertilization (**Figure 2**) study. The rice straw treatment had a higher accumulation rate of organic matter (0.34 g kg^{-1} yearly) than the pig manure treatment (0.14 g kg^{-1}) probably due to the higher amount of C and C/N ratio of the former.

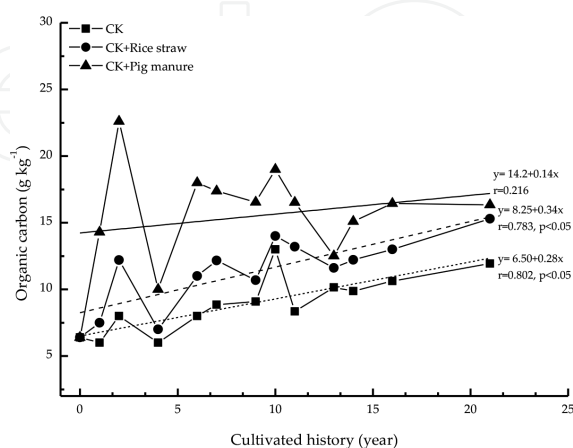


Figure 2. Changes of soil organic matter in the upland red soil as affected by the long-term application of organic–inorganic fertilizers (1988–2009).

4.3. Soil nitrogen, phosphorus, potassium

Compared with the initial value in 1988, soil total nitrogen (TN) showed a significant increasing trend during the long-term fertilization (**Figure 3**). Both RS and PM treatments significantly increased soil TN content compared to the CK, but PM treatment was more effective in the accumulation of TN in the upland red soil.

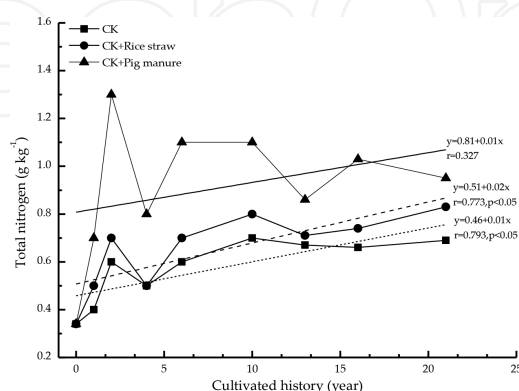


Figure 3. Changes of soil total nitrogen in the upland red soil as affected by the long-term application of organic-inorganic fertilizers (1988–2009).

The upland red soil in this study is a typical acidic soil and characterized by its strong P-fixation capacity and low P availability due to the high content of aluminum and/or iron oxides, which can convert P in the soil solution to water-insoluble Fe-Al-P. Compared with the CK, rice straw addition was not significant in improving soil total phosphorus (TP) and Olsen-P, but the addition of pig manure did significantly increase soil TP and Olsen-P by 28.4–116.7% and 292.6–731.8%, respectively (**Figure 4**). There is a significant positive correlation between soil TP content and the year of cultivation ($r = 0.843$, $p < 0.05$). Based on this relationship, the soil TP content in the PM treatment was increased by 30 mg kg⁻¹ yearly.

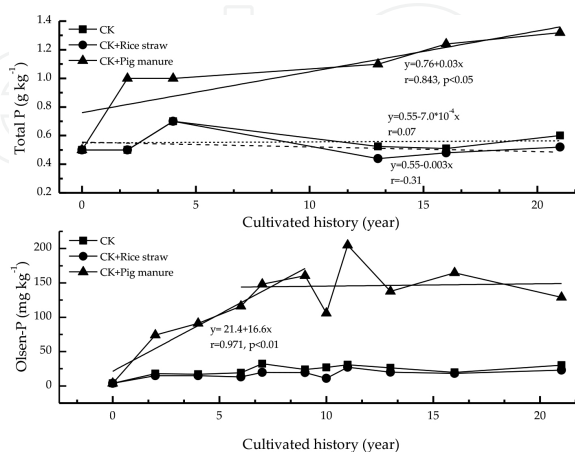


Figure 4. Changes of soil total phosphorus (P) and Olsen-P in the upland red soils as affected by the long-term application of organic-inorganic fertilizers (1988–2009).

During the long-term fertilization study, soil potassium (K) in the upland red soil significantly decreased at the rate of 50 or 60 mg kg⁻¹ yearly and there was no significant difference among the three treatments (**Figure 5**). Compared with their initial values in 1988, soil total K was reduced by 1.9–12.0%, 2.8–9.3% and 0.9–14.0% in the CK, RS, and PM, respectively (**Figure 5**). The K reduction is probably due to plant uptake and removal or leaching losses.

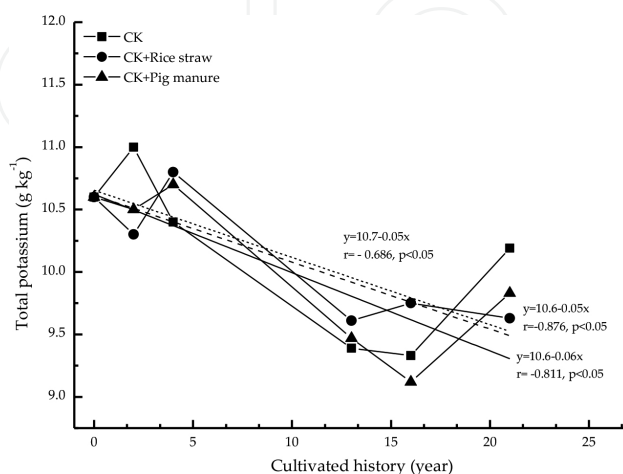


Figure 5. Changes of soil total potassium (K) in the upland red soil as affected by the long-term application of organic–inorganic fertilizers (1988–2009).

4.4. Soil aggregate structure

Soil aggregate formation and stability are the results of complex interactions among biological, chemical, and physical processes in the soil, which are also important determinants of soil fertility and productivity. Distribution or/and redistribution of various sized soil aggregates in the upland red soil could be significantly affected by the long-term application of organic–inorganic fertilizers (**Figure 6**, [15]). The distribution of dry-sieved aggregates (DSA) in the upland red soil showed similar trends among CK, RS, and PM in the order of (>5) $>1-0.25 > 5-2 > 0.25-0.05 > 2-1 > (<0.053 \text{ mm})$, whereas the distribution of water-stable aggregates (WSA) was in the order of $0.25-0.053 > 1-0.25 > (>5) > (<0.053) > 5-2 > 2-1 \text{ mm}$ (**Figure 5**). Compared with the CK, addition of rice straw and pig manure significantly increased the proportion of DSA in $1-0.25$, $0.25-0.053$, and $<0.053 \text{ mm}$ fractions. No change in the $2-1 \text{ mm}$ fraction, however, was detected. Addition of rice straw significantly decreased the proportion of WSA in the $>5 \text{ mm}$ fraction and increased the proportion of WSA in $2-1$ and $1-0.25 \text{ mm}$ fractions but did not affect the $1-0.25 \text{ mm}$ aggregate fraction (**Figure 6**). Evidently, there was a significant difference between the effect of rice straw addition and pig manure amendment on aggregate size distribution in the upland red soil.

Overall, 86.9–93.8% of DSA and 47.4–50.0% of WSA were in the macro-aggregate ($>0.25 \text{ mm}$) fraction in the upland red soil after 22 years of combined application of NPK fertilizer and organic amendments (**Figure 6**). Compared with the CK treatment, addition of rice straw and pig manure increased the proportion of the $>0.25 \text{ DSA}$ fraction by 4.9 and 7.9%, respectively;

and only the addition of pig manure significantly increased WSA by 5.9% in the >0.25 mm fraction (Figure 7).

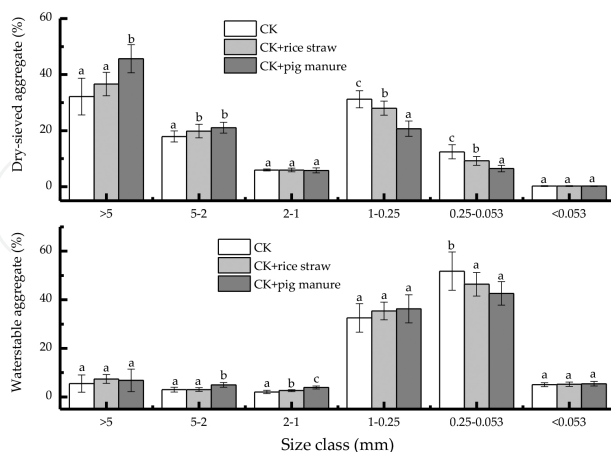


Figure 6. Distribution of dry-sieved aggregates (DA) and water-stable aggregates in the upland red soil impacted by long-term fertilization (1988–2009). Same lowercase letters indicate no significant difference at $p < 0.05$ between different fertilizer treatments.

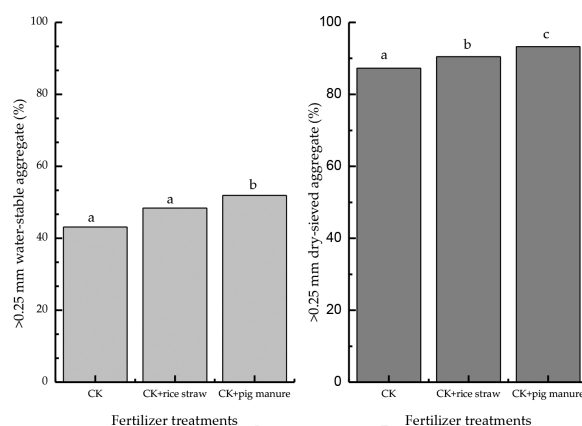


Figure 7. Proportion of macro-aggregate (>0.25 mm) in the upland red soil impacted by the long-term fertilization treatment (1988–2009). Same lowercase letters indicate no significant difference at $p < 0.05$ between different fertilizer treatments.

5. Sustainable development and nutrient management of red soil

Red soils are usually low in pH, nutrients, and organic matter content, and difficult to cultivate because of its poor physical condition and low water-holding capacity. Therefore, the productivity of the red soils is low under natural conditions. Most farmers have livestock or poultry production on the side in the red soil region, and they use the grain to feed the animal and use the manure to improve soil productivity. Although combined application of chemical fertilizer and rice straw or pig manure was an effective method to improve soil fertility (Figures

3 to 5), soil macro-aggregates (**Figures 6 and 7**), and soil organic matter content (**Figure 2**), it could result in N and P accumulation and soil acidification in the long term (**Figure 1**). The accumulation of P in the soil may result in high risk of P losses to the environment [16]. Therefore, it is imperative to monitor nutrient balance when large quantities of organic amendments are used. This study showed that it only took 4–5 years of applying phosphate fertilizer alone, 2 years when organic-chemical fertilizers were applied simultaneously to increase Olsen-P to over 20 mg P kg⁻¹ (sufficiency level) (**Figure 4**). When soil P is sufficient for plant growth, continuous application of P fertilizer including organic manure not only hurt farmer's economic return but also contributing to non-point source pollution. Therefore, better nutrient management strategy needs to be developed and disseminated to farmers in the region in order to prevent potential environmental risk from crop production.

Better soil quality is generally associated with greater concentrations of soil organic matter and a plentiful supply of essential mineral elements. Thus, the recycling of organic matter and mineral elements from crop residues and animal manure to soil often benefits agricultural sustainability. Red soil production under long-term fertilization is perceived to be environmentally friendly, but P accumulation and acidification in the PM may lead to faster degradations of soil quality than in the CK and may be an important cause of eutrophication in water bodies (**Figures 1 and 4**).

Soil acidification is an important cause of soil degradation. Generally, soil acidification is a slow process under natural conditions over hundreds to millions of years, because soils are strongly buffered by ion exchange reactions, the weathering of soil minerals, and interactions with aluminum and iron in the acidic range [17]. However, this process in red soils is accelerated by the addition of crop straw and animal manure; and soil acidification appeared only after 7 cultivation years (**Figure 1**). Generally, strategies for the application of organic manure have been based on meeting crop N needs to maximize plant growth and minimize nitrate loss by leaching, a potential groundwater contaminant [18]. Guo et al. (2010, [19]) showed that severe soil acidification in China's croplands occurred, and attributed it to the combination of high-N fertilizer inputs, plant uptake, and removal of base cations from soils, and acid deposition, with the dominant effect from the overuse of N fertilizer. But, soil is a mixture of acid/base systems, so there are many causes of soil acidification in addition to N-induced acidification.

Most of organic manures often contain significant amounts of low-molecular-weight organic acids due to decomposition of large quantities of organic matter input, which could be another reason for the accelerated P accumulation and soil acidification [16]. Many organic acids contain carboxyl and hydroxyl groups, and possess negative charge, which strongly competes for the adsorption sites with phosphate [20, 21]. Manure can also change soil pH and thus alter soil P availability. Guo et al. (2010, [19]) pointed out that soil could be acidified by the excessive application of farmyard manure. But the mechanisms of manure-induced P accumulation and P accumulation-induced soil acidification still need further investigation [18], especially in the red soil with strong P fixation capacity. Maintaining stable levels of production and quality under fertilization without compromising economic profitability or the environment is an important guarantee of agricultural sustainability. Therefore, new strategies of using both

commercial fertilizers and animal manure must be established to prevent P buildup and to minimize acidification in the red soil region.

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Author details

Yanling Wang^{1*} and Hailin Zhang²

*Address all correspondence to: ylwang@nuist.edu.cn

1 International Center for Ecology, Meteorology & Environment, School of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, China

2 Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK, USA

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