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RESEARCH ARTICLE

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Effects of phosphate fertilizer and manure on Chinese cabbage yield and soil phosphorus accumulation

Abstract The yield response of Chinese cabbage to phosphate fertilizer and manure was studied. The effect of over-application of phosphate fertilizer and manure on plant total phosphorus content and phosphorus accumulation in soil was also investigated. The experiment was arranged in a plastic barrel in the field for two years. Application of phosphate fertilizer at the rates of 150–600 mg·kg^{-1} gave a yield increase of 14.9%–21.5% of Chinese cabbage. Application of manure at the rates of 33.3–133.2 g·kg^{-1} gave a yield increase of 18.2%–25.9% of the crop. There was no significant difference of yield response at the rates of 150, 300 and 600 mg·kg^{-1} phosphate fertilizer, and no significant yield response to the application of phosphate fertilizer after applying manure. The total P content in Chinese cabbage was increased gradually with the rate increase of phosphate fertilizer and manure. Phosphorus was absorbed luxuriously by the plant with over-application phosphate fertilizer and manure. The content of total-P, Olsen-P, water-soluble P, biological available P in the soil was increased with the rate of phosphate fertilizer and manure. Organic phosphorus in the soil was increased by the application of manure. Olsen-P had high correlations with water-soluble-P and biological available-P, but there was a poor relationship between Olsen-P and organic-P.

Keywords phosphate fertilizer, organic manure, response of yield, residual phosphorus, Chinese cabbage

1 Introduction

Phosphorus in the agricultural soils in China was increased by 11% annually from 1981 to 2000, with an averaged total P and Olsen-P of 210 mg·kg^{-1} and 6–8 mg·kg^{-1}, respectively (Lu, 2003). Soil P is in surplus status both in southern China and northern China where wheat and corn are rotated. Long-term in situ experiments demonstrated that soil phosphorus accumulation has amounted to 38.4 kg·hm^{-2} and the concentration of Olsen-P has increased by 1.3 mg·kg^{-1} every year, when phosphate application reached 135 kg·hm^{-2} (P_2O_5), with an average yield of 8653 kg·hm^{-2} (Lu et al., 2000; Liu and Zhang, 2000). In sheltered production system, approximately 50% of P comes from inorganic phosphate fertilization, P application rate is 2.3–33.5 times greater than the demand of vegetables (Liu et al., 2004); Olsen-P level and total P level have a significantly positive correlation with phosphate fertilizer application (Liu et al., 2005). Recently, the effectiveness of phosphate fertilization is dropping down while the environmental risk is increasing due to phosphorus accumulation in soils associated with phosphate excessive application (Zhang et al., 2004). Therefore, how to enhance the effectiveness of phosphate fertilization and protect the environment is becoming an imperative issue.

Evaluating rational fertilizer application of the crop is generally based on the principle and technology of nutrients-balanced recommendation. During the 1980s and the 1990s, P application rate was determined by target yield method or function of the yield response of crops to fertilizer (Li, 1985; Chen and Li, 1984), however, these two methods did not consider the impact of P on the environment. When the soil fertility was low, high phosphate fertilization was required to meet the crops growth, and it was not an issue of the environment. Since the 1990s, due to the enhancement of soil fertility in China, dealing with the problem of maintaining soil productivity and reducing the environmental load has become increasingly urgent (Zhang et al., 2004).

A long-term fertilizer experiment has taken an important part in estimating the amount of phosphate fertilizer since the 1980s. Because the experiment design often includes N, P, K and manure factors, and 2–3 levels are designed for each factor, phosphate application is 90–180 kg·hm^{-2} (Lin et al., 1994), which is far lower than

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the actual application in sheltered agriculture. Many efforts have been made to assess the environmental risk from P accumulation in agricultural soils, and soil test P is used widely as an indicator (Sharpley et al., 2001; Sims et al., 2000), however, no consistent conclusion has been drawn due to inconsistent impact of soil phosphorus level, phosphate application rate and types (inorganic and organic) on these P parameters. For example, good correlations between soil total P, Mehlich-III P and water-soluble P were summarized, therefore, total soil P and Mehlich-III P were considered as indicators for guiding the P application and evaluating the environmental risk of soil P. However, the correlation is poor after manure application, and Mehlich-III P increases while water-soluble P decreases. Therefore, soil test P and runoff P are suggested as alternative indicators under these situations (Sharpley et al., 2004). Delaune demonstrated that Mehlich-III P is related to soluble reactive P in runoff water positively before manure application. However, after manure application, no relationship between Mehlich-III P and soluble reactive P is found in the runoff water. He suggested that soil available P couple with the soluble reactive P in runoff water as the parameter for the environmental risk (Delaune et al., 2004a). Moreover, due to the huge difference of P saturated absorption among different P level soils, it is hard to assess P environmental risk using Olsen-P. Water-soluble P can be used as an indicator, Which has a low absorption in soils (Börling et al., 2004). Sims et al. (2000) declared that the soil test P can be used as an indicator for evaluating the capacity of phosphorus supply and P fertilizer application. The different phosphorus forms can reflect not only the capacity of phosphorus supplying but also the environment risk from agriculture (Saleque et al., 2004). It is thus very difficult to provide a full assessment using any single indicator. Overall, several long-term practices have been developed to study the yield response, accumulation of different phosphorus forms and the environmental risk of accumulated P.

This study is to evaluate the impact of phosphate fertilizer and straw manure on the following aspects: (1) Chinese cabbage yield; (2) organic phosphorus, Olsen-P, water-soluble P and biological available P and; (3) the correlations between the above P forms in soils. The results from these studies are used to guide the rational phosphate fertilizer and manure application together with protecting the agricultural environment.

2 Methods

2.1 Experimental site

This study was carried out in the Experimental Farm of the Agricultural University of Hebei, Baoding, China from 2003 to 2004. Experimental soil was aquic-cinnamon soil, and its properties are shown in Table 1. Qiulü-75, one common Chinese cabbage variety, was used in the experiment.

2.2 Experimental design

This experiment was carried out with a complete orthogonal design. The four phosphate fertilizer rates were 0 mg·kg^{-1} (P_0), 150 mg·kg^{-1} (P_1), 300 mg·kg^{-1} (P_2), and 600 mg·kg^{-1} (P_3), the four manure rates of N were 0 g·kg^{-1} (M_0), 33.3 g·kg^{-1} (M_1), 66.7 g·kg^{-1} (M_2), and 133.3 g·kg^{-1} (M_3) and K application rates were 540 kg·hm^{-2}. P, K and 1/3 N were applied as basal dressing and 1/3 N at cross-stage and 1/3 at extending stage. Manure was applied in 2003. Chinese cabbages were planted on August 12–15 in 2003 and 2004, and were harvested and weighted separately for each pot on November 10–20 in 2003 and 2004.

Applied fertilizers were phosphate fertilizer (K_2HPO_4, CaH_2PO_4), N fertilizer ($CO(NH_2)_2$), K fertilizer (K_2HPO_4, K_2SO_4) and manure (Decomposed straw with N 1.35%, P_2O_5 0.63%, K_2O 1.90%, C 35.0%).

Plastic pots with a 20-cm diameter and 40-cm depth were used in the experiment. Experimental soil was mixed through a 2-mm sieve. The bottom layer soil (20–40 cm, 11 kg soil) in each experimental pot was filled with the original soil, while the top layer soil (0–20 cm, 20 kg soil) in each pot was filled with fertilized soils (inorganic P fertilizer and straw manure).

2.3 Soil and plant analyses

The representative sample of Chinese cabbage in each pot was oven dried at 60°C after harvest and grilled for total P analysis. Total P was digested with HNO_3 and 30% H_2O_2. Meanwhile, the soil was randomly sampled from top layer (0–20 cm), then every six sample soils were mixed as one sample.

The soil test P included Olsen-P, water-soluble P, and biologically available P. Olsen-P was extracted by 0.5 mol·L^{-1} $NaHCO_3$ with a ratio of solution/soil (20:1) on an end-over-end shaker for 30 min.

Soil total P was digested by using HNO_3 and $HClO_4$.

Organic P was extracted by heating samples at 550°C for 2 h and cooling soils with 1 mol·L^{-1} H_2SO_4. Organic P was calculated based on the difference between inorganic P in the heated and cooled samples, while residual P was calculated according to the difference between total soil P and inorganic P in the heated samples.

Water-soluble P ($CaCl_2$-P) was extracted by using 0.01 mol·L^{-1} $CaCl_2$ at a solution/soil ratio of 10:1 during 60 minutes on an end-over-end shaker (Maguire and Sims, 2002).

Biologically available P (NaOH-P) was extracted with 0.1 mol·L^{-1} NaOH at a solution/soil ratio of 500:1 on an end-over-end shaker during 24 h (Walf and Baker, 1985).

Table 1 Properties of experimental soils

total N/g·kg^{-1}	organic matter /g·kg^{-1}	NaOH-hydrolyzable N/mg·kg^{-1}	exchangeable K/mg·kg^{-1}	total P /mg·kg^{-1}	organic-P /mg·kg^{-1}	Olsen-P /mg·kg^{-1}	water-soluble P/mg·kg^{-1}	biological available P/mg·kg^{-1}
1.00	10.80	77.6	170.9	678	102	20.1	1.5	60.0

The P contents in the above solutions were determined colorimetrically using the automatic ascorbic reduction (Bao, 1981).

Statistical analyses were carried out using the Statistical Analysis System (SAS system) for windows V8.

3 Results

3.1 Effects of phosphate fertilizer and manure on Chinese cabbage yields

Impacts of phosphate fertilizer and manure on cabbage yield were significant (Table 2). Phosphate fertilization (150–600 mg·kg^{-1}) and manure (33.3–133.3 g·kg^{-1}) increased the cabbage yields by 14.9%–21.5% and 18.2%–25.9%, respectively. However, the yields of three phosphate fertilization levels (150, 300 and 600 mg·kg^{-1}) had no significant difference, similarly between three manure levels. In addition, negative interaction effects between phosphate fertilization and manure indicated no significant impacts of excessive phosphate fertilization and manure on Chinese cabbage yields.

3.2 The balance of input and output phosphorus in soils

Total phosphorus of Chinese cabbage increased significantly with increasing phosphate fertilization and manure (Table 3). Total P in the cabbage at 150–600 mg·kg^{-1} phosphate fertilizer application was increased on average by 15.8%, which is contrary in the control; significant influence of phosphate fertilization coupled with manure application was also found; however, no significant influence from manure on total phosphorus was found. These proved that heavy phosphate application can result in Chinese cabbage uptaking excessive phosphorus.

Within phosphate fertilization treatments (150–600 mg·kg^{-1}), approximately 82.8%–91.4% of phosphorus accumulation came from phosphate input due to the excessive application (Table 4). While within manure treatments, approximately 56.3%–86.9% of P was from phosphorus input. It is indicated that the amount of accumulate phosphorus may increase with phosphate fertilizer and manure application.

3.3 Impacts of phosphate fertilization and manure on different soil phosphorus forms

Phosphate fertilization and manure application increased significantly Olsen-P level (Table 5). In contrast with the original soils, Olsen-P level of phosphate fertilization treatments increased by 10.9–82.0 mg·kg^{-1}, which accounted for 8.3%–15.0% of the total phosphorus accumulation; Similarly when straw application was at 133.3 mg·kg^{-1}, the increase of Olsen-P accounted for 8.2% while the ratio increased to 13.1%–21.9% (mean 17.4%) at phosphate fertilization coupled with manure application. Moreover, a strong positive linear relationship existed between the amount of accumulated phosphorus and the concentration of Olsen-P ($y = 0.082x + 14.4$, x represents P (mg·kg^{-1}) and y represents Olsen-P (mg·kg^{-1}), $r = 0.8400^{**}$). It indicated that excessive phosphate application including inorganic and straw may lead to phosphorus accumulation in soil.

Soil organic phosphorus was highly related to manure application but poorly to phosphate fertilization. In contrast to the original soil, soil organic P was significantly increased by 61.9 mg·kg^{-1} in the pot with 133.3 mg·kg^{-1} manure, and organic P accumulation accounted for 16.5%–39.4% of the total phosphorus accumulation. It is indicated that excessive phosphate application may increase inorganic phosphorus accumulation while manure application may significantly increase organic P pool.

The influence of phosphate fertilization and manure application on different soil phosphorus forms was similar (Table 6). Water-soluble P and biologically available P

Table 2 The yield response of Chinese cabbage to phosphate fertilizer and decomposed straw (g·pot^{-1})

treatment	2003				2004				mean			
	P_0	P_1	P_2	P_3	P_0	P_1	P_2	P_3	P_0	P_1	P_2	P_3
M_0	1932	2263	2423	2300	2090	2416	2219	2330	2036 A(A*)	2340 B(B)	2425 B(B)	2473 B(B)
M_1	2096	2645	2888	2456	2545	2929	2360	2535	2407 B(A)	2562 C(B)	2528(Bb)	2666 C(c)
M_2	2317	2800	2775	2752	2365	2810	2687	2755	2386 Bb(A)	2840 D(Bb)	2989 C(c)	2753 C(d)
M_3	2738	2910	2890	2678	2540	2537	3053	2585	2564 c(A)	3115 F(B)	3040 C(B)	2897 D(C)

Note: Significant differences at P=0.05 and P=0.01 are represented by different small letters and different capital letters, respectively. Letters in parentheses represent the difference of the same row, letters out of parentheses represent the difference of the same line. The same as below.

Table 3 Effects of phosphate fertilizer and manure on the total phosphorus of Chinese cabbage (%)

treatment	P_0	P_1	P_2	P_3
M_0	0.495A(A)	0.541 B(B)	0.562 B(B)	0.617 C(C)
M_1	0.502A(A)	0.552 B(B)	0.590 C(C)	0.619 C(D)
M_2	0.481A(A)	0.571 B(B)	0.639 D(C)	0.644 D(C)
M_3	0.487A(A)	0.624 C(B)	0.645 D C)	0.708 E(D)

Note: Capital letters mean different at $P<0.01$ level and capital letters inside or outside of parentheses represent significantly different of row and significantly different of line, respectively.

are highly related to the P fertilization and manure application. In contrast to the original soil, water-soluble P and biologically available P of application rate at 600 mg·kg^{-1} increased by 3.7 and 80.1 mg·kg^{-1}, which accounted for 0.8% and 14.6% of the total P accumulation, respectively. Approximately water-soluble P and biologically available P of 133.2 mg·kg^{-1} increased by 0.4 and 35.7 mg·kg^{-1}, which accounted for 0.3% and 22.4% of the total P accumulation. Also, the high correlations between Olsen-P, water-soluble P and biologically available P can be described by $y_1 = 0.09x - 1.0$ ($r_1 = 0.9666^{**}$) and $y_2 = 1.21x + 42.6$ ($r_2 = 0.9317^{**}$), where x represents soil Olsen-P, y_1 represents water-soluble P and y_2 represents biologically available P. Therefore, excessive phosphate application including inorganic and organic could lead to a significant increase of water-soluble P and biologically available P.

4 Discussion

4.1 Soil phosphorus supply capacity and reasonable phosphate fertilization

The nutrient-balanced recommendation method is based on the capacity of soil phosphorus supply and target demand of crops. With the prerequisite of maintaining soil productivity and protection of the environment, the determination of reasonable phosphate application rate should mainly depend on the effectiveness of phosphate fertilizer, soil phosphorus accumulation, different phosphorus forms and environmental risk based on the long-term in situ experiment. In this study, when the phosphate application rate was 150 mg·kg^{-1}, and straw application rate was 33.3 mg·kg^{-1}, yields increased by 14.9% and 18.2%, respectively, thus the soil supply capacities were 85.1% and 81.8%, which indicated that phosphorus was apparently surplus at 23.4 mg·kg^{-1} and 75.0 mg·kg^{-1}, but the phosphorus accumulation was 142.2 mg·kg^{-1} and 25.8 mg·kg^{-1}, provided that the soil supply capacity of phosphorus was considered. Therefore, for the soil with high phosphorus supply capacity, it is unfit to use the P balance between input and output, probably leading to the excessive phosphate application rate.

It was also indicated that heavy phosphate application may lead to phosphorus excessive uptake, which might be the reason for high phosphorus use efficiency without

Table 4 Phosphorus accumulation of phosphate fertilization and manure application (2-year average) (kg·hm^{-2})

items	input P				output P				accumulated P *			
	P_0	P_1	P_2	P_3	P_0	P_1	P_2	P_3	P_0	P_1	P_2	P_3
M_0	0	150.0	300.0	600.0	100.8	126.6	136.3	152.6	0.0	124.2	264.5	548.2
M_1	45.8	195.8	345.8	645.8	120.8	141.4	149.1	165.0	25.8	155.2	297.5	581.6
M_2	91.6	241.6	391.6	691.6	114.8	162.2	191.0	177.3	77.6	180.2	301.4	615.1
M_3	183.2	333.2	483.2	783.2	124.9	194.4	196.1	205.1	159.1	239.6	387.9	687.9

Note: Accumulated P = input P + provided P by soil.

Table 5 Effects of phosphate fertilizer and manure on Olsen-P and organic-P in soil (mg·kg^{-1})

treatment	Olsen-P				organic-P			
	P_0	P_1	P_2	P_3	P_0	P_1	P_2	P_3
M_0	13.2a(A)	31.0A(B)	42.0A(C)	102.1A(D)	99.9A	103.8 a	105.0 a	103.4 a
M_1	18.9a(A)	40.4A(B)	65.4B(C)	116.2B(D)	119.0A	129.0 b	120.6 A	111.9 a
M_2	22.3a(A)	55.5B(B)	72.5Cc(C)	145.6C(D)	130.8A	132.2 bB	143.2 B	143.8 bB
M_3	33.1b(A)	58.2B(B)	83.4d(C)	171.0D(D)	163.9B	196.5C	175.4C	185.5C

Table 6 Effect of the application of phosphate fertilizer and manure on water-soluble P and biologically available P (mg·kg^{-1})

treatments	water-soluble P				biologically available P			
	P_0	P_1	P_2	P_3	P_0	P_1	P_2	P_3
M_0	0.7A(A)	1.8A(B)	2.0A(B)	5.2A(C)	49.7A(A)	73.4A(B)	83.0A(C)	140.1A(D)
M_1	1.2B(A)	2.3B(B)	4.7B(C)	7.4B(D)	59.2B(A)	104.4B(B)	116.3D(C)	192.5B(D)
M_2	1.5Bb(A)	3.9C(B)	5.1C(C)	13.3C(D)	75.0C(A)	109.2B(B)	136.9C(C)	205.2C(D)
M_3	1.9c(A)	5.3D(B)	8.1D(C)	15.0D(D)	95.7D(A)	125.8C(B)	173.5D(C)	217.9D(D)

significant yield responses. For example, when phosphate application rates were 150, 300 and 600 mg·kg^{-1}, no significant difference of yields between these treatments were found, but in contrast with the control, the total P content of Chinese cabbage of these three treatments were increased by 9.3%, 13.5% and 24.7%, and the apparent phosphorus use efficiency of these three treatments was 17.2%, 11.8% and 8.6%, respectively. This may explain the above phenomenon. In addition, between these three treatments, the increases of yields were 200, 130 and 70 g per unit P (100 mg in this study). Therefore, for the soils with high phosphorus supply capacity, determination of phosphate application rate based on yield increase per unit is viewed as an objective strategy.

4.2 Environmental risk of P accumulation in soils

It has been demonstrated that the soil phosphorus in a super saturated status due to the long-term excessive phosphate application, therefore, may lead to a high runoff risk from agricultural soils (Koopmans et al., 2004; Nair et al., 2004). This is confirmed in this study, for example, soil Olsen-P and its percentage of total accumulation P increased with phosphate application rate.

Our study proves that soil Olsen-P has a high correlation with water-soluble P and biologically available P. Meanwhile, Olsen-P is an effective indicator that quantifies the soil phosphorus supply capacity and determines phosphate application rate. The phosphorus forms indicate not only the availability of soil P, but also the risk to water body (Bowman and Vigil, 2002). Kleinman et al suggested water-soluble P as an indicator for runoff P in agricultural soils (Börling et al., 2004; Kleinman et al., 2002), but more studies showed that soil available P is a better indicator (Sims et al., 2000; Mallarino and Atia, 2005). Sharpley reported the correlation between Mehlich-III P and the P in runoff more than water-soluble P after manure application, and thus suggested Mehlich-III P as an indicator for evaluating the P runoff from agricultural soils (Sharpley et al., 2004). Recently, Delaune has demonstrated that Mehlich-III P is related to soluble reactive P in runoff water positively before manure application, however, after the manure application such as beef, poultry, swine manure or decomposed straw manure, soil available P is related positively to P release from inorganic and organic fertilizers, while there is no relationship between Mehlich-III P and soluble reactive P in the runoff water. Because the P- index is highly related to the soluble reactive P in runoff water, he indicates that soil available P is not sensitive to quantifying the runoff risk from agricultural soils but P index is (Delaune et al., 2004b). Furthermore, Leytem et al. (2003) has found that P- index may change with the amount of manure, therefore P-index may be modified according to the quantity of manure and rational application of manure can be suggested to control the risk from agriculture P.

As shown in this study, due to the increase of soil organic P, water-soluble P, Olsen-P and biologically available P with phosphate application rate, a high environmental risk of P is also associated with organic fertilizer application. The impact of C/N ratio of organic fertilizer on environmental risk needs to be further investigated. In this study, water-soluble P and biologically available P may increase with the P fertilizer and decomposed straw application and there are significant correlations in the three forms. Because they are widely used to represent the capacity of soil supply phosphorus, we suggest Olsen-P as the index to recommend rational phosphate application and evaluate the environmental risk from agricultural phosphorus.

5 Conclusion

Phosphate fertilization and manure application increased the Chinese cabbage yield, phosphate fertilization and manure increased cabbage yields by 14.9%–215% and 18.2%–25.9%, respectively. However, no significant difference was found when phosphate application rate was greater than 150 mg·kg^{-1}.

Positive correlation between phosphate application rate and total P of Chinese cabbage was obtained, therefore, it proved that Chinese cabbage may uptake excessive phosphorus.

Olsen-P, water-soluble P and biologically available P can significantly increase with phosphate fertilization and manure. In contrast to the original soils, Olsen-P with phosphate application may increase by 10.9–82.0 mg·kg^{-1}, which accounts for 8.3%–15.0% of total phosphorus accumulation, while the ratio increases to 13.1%–21.9% of phosphate fertilization coupled with manure application. Similarly, water-soluble P and biologically available P of application rate of 600 mg·kg^{-1} increased by 3.7 and 80.1 mg·kg^{-1}, which accounts for 0.8% and 14.6% respectively. Soil organic P may increase only with manure application.

Olsen-P is highly related to soil phosphate accumulation, water-soluble P and biologically available P, so Olsen-P can be used as an indicator for guiding the phosphate application and evaluating the environmental risk of soil phosphorus.

References

Börling K, Otabbong E, Barberis E (2004). Soil variables for predicting potential phosphorus release in Swedish norcalcareous soils. Journal of Environmental Quality, 33(1): 99–106

Bao S D (1981). Soil and Agricultural Chemistry Analysis. Beijing: China Agriculture Publishing House, 76–82 (in Chinese)

Bowman R A, Vigil M F (2002). Soil testing for different phosphorus pools in cropland soils of the Great Plains. Journal of Soil and Water Conservation, 57(6): 479–485

Chen L S, Li R G (1984). The Principles and Practices of Applying Fertilizer on Cropland. Beijing: China Agriculture Publishing House, 91–104 (in Chinese)

Delaune P B, Moore Jr P A, Carman D K, Sharpley A N, Haggard B E, Daniel T C (2004a). Development of a phosphorus I index for pastures fertilized with poultry litter-factors affecting phosphorus runoff. Journal of Environmental Quality, 33(6): 2183–2191

Delaune P B, Moore Jr P A, Carman D K, Sharpley A N, Haggard B E, Daniel T C (2004b). Evaluation of the phosphorus source component in the phosphorus index for pastures. Journal of Environmental Quality, 33(6): 2192–2200

Kleinman P J A, Sharpley A N, Wolf A M, Beegle D B (2002). Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. Soil Science Society of America Journal, 66(6): 2009–2015

Koopmans G F, Chardon W J, Willigen P D, Riemsdijk W H V (2004). Phosphorus desorption dynamics in soil and the link to a dynamic concept of bioavailability. Journal of Environmental Quality, 33: 1393–1402

Leytem A B, Sims J T, Coale F J (2003). On-farm evaluation of a phosphorus site index for Delaware. Journal of Soil and Water Conservation, 58(2): 89–97

Li R G (1985). Function of the Yield Response of Crops to Fertilizer. Beijing: China Agriculture Publishing House, 76–83 (in Chinese)

Lin B, Lin J X, Li J K (1994). The changes of crop yield and soil fertility with long-term fertilizer application. Plant Nutrition and Fertilizer Science, 1: 6–18 (in Chinese)

Liu J L, Zhang F C (2000). The change of soil P by applied P fertilizer and manure in long-term rotation experiment II, the change of Olsen-P and inorganic phosphorus. Chinese Journal of Applied Ecology, (11)3: 365–368 (in Chinese)

Liu J L, Liao W H, Zhang F H, Gao Z L (2004). Change in different phosphorus pool and distribution in soil profile of vegetable field. Journal of Agricultural University of Hebei, (27)6: 6–11 (in Chinese)

Liu J L, Li R G, Liao W H, Jia K, Meng N, Cui Z (2005). The yield response of vegetable to phosphate fertilizer and soil phosphorus accumulation in Chinese cabbage. Scientia Agricultura Sinica, 38(8): 1616–1620 (in Chinese)

Lu R K, Shen Z Y, Shi J P (2000). Nutrient balance of agroecosystem in six provinces in southern China. Scientia Agricultura Sinica, 33(2): 63–67 (in Chinese)

Lu R K (2003). The phosphorus level of soil and environmental protection of water body. Phosphorus & Compound Fertilizer, 18(1): 4–8 (in Chinese)

Maguire R O, Sims J T (2002). Soil testing to predict phosphorus leaching. J Environment Quality, 31:1601–1609

Mallarino A P, Atia A M (2005). Correlation of a resin membrane soil phosphorus test with corn yield and routine soil tests. Soil Science Society of America Journal, 69(1), 266–272

Nair V D, Portier K M, Graetz D A, Walter M L (2004). An environmental threshold for degree of phosphorus saturation saturation in sandy soils. Journal of Environmental Quality, 33(1):107–113

Saleque M A, Naher U A, Islam A, Pathan A B M B U, Hossain A T M S, Meisner C A (2004). Inorganic and organic phosphorus fertilizer effects on the phosphorus fractionation in wetland rice soils. Soil Science Society America Journal, 68: 1635–1644

Sharpley A N, McDowell, R W, Weld J L, Peter J A K (2001). Assessing site vulnerability to phosphorus loss in an agricultural watershed. Journal of Environmental Quality, 30(6): 2026–2036

Sharpley A N, McDowell R W, Peter J A K (2004). Amount, forms, and solubility of phosphorus in soils receiving manure. Soil Science Society of America Journal, 68(6): 2048–2057

Sims J T, Ewards A C, Schoumans O F, Simard R R (2000). Integrating soil phosphorus testing into environmentally based agricultural management practices. Journal of Environmental Quality, 29(1): 60–71

Walf A M, Baker H B (1985). Soil tests for estimating labile-soluble and algae-available phosphorus in agricultural soils. Journal of Environmental Quality, 14(3): 341–348

Zhang W L, Wu S X, Ji H J, Kolbe H (2004). Estimation of agricultural non-point source pollution in China and the alleviating strategies I. Estimation of agricultural non-point source pollution in China in early 21st century. Scientia Agricultura Sinica, 34(7): 1008–1017 (in Chinese)