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Research Article

Influence of N and P Applications on Phosphorus Leaching in Salt-affected Soils of the North China Plain

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Abstract

Background and Objective: The reclaimed salt-affected soils of the North China plain are an important land resource. The primary objective of this study was to investigate the effects of long-term fertilization practices on phosphate leaching so that practical advice on phosphorous fertilizer applications could be provided to farmers. Results from this long-term study have implications for P accumulation and loss in salt-affected soils around the globe where saline soils are present. **Materials and Methods:** Phosphorus (P) accumulation and leaching in the salt-affected soils of the North China Plain for 24 years has been studied. The field experiment with different applications of P and nitrogen (N) began in 1983. Soil samples were collected from 4 layers (0-20, 20-40, 40-60 and 60-100 cm layer, respectively) after the harvest of maize in 2007. **Results:** The total P content tended to stabilize at 0.40-0.60 g kg^{-1} in 0-20 cm layer with natural vegetation in the absence of P fertilizer. The content of reactive P increased significantly from 0.5-1 in 1970's to 6.40-8.60 mg kg^{-1} in 2007 in the control plot. With application of fertilizers, the contents of total P and reactive P increased to 0.96 and 43.24 mg kg^{-1} in the 0-20 cm layer, respectively. Both the application rate of P and N/P ratio influenced P leaching from 0-20 to 20-40, even to the 60-100 cm layer. **Conclusion:** Based on these results, it was suggested that P application rate at 135 kg P ha^{-1} is appropriate to maintain the P requirements by plants while minimizing P leaching.

Key words: Fertilization, leaching, phosphorus, long-term study, salt-affected soil, field experiment, N/P ratio

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Phosphorus (P) is an essential nutrient for crop production. Phosphorus accumulation in soils has been increasing with long-term continuous application of P fertilizers in China, because P use efficiency is generally low in the year of application[1-3]. In the early stage of excessive P application, P accumulation in soil was not considered a significant environmental problem. This was because most soils strongly adsorb P, especially in regions where soils were low in P and there was low rainfall or irrigation, or in non-agricultural soils.

On the other hand, in areas of intensive crop production with continuous P application, P loss from surface soil has been reported[2,4,5]. McDowell *et al.*[6] monitored P concentrations in drainage water in pipe-drains (at 65-cm depth) from soils with Olsen P content ranging from 7-110 mg kg^{-1} and found that the critical value for P leaching loss was Olsen P $\geq$57 mg kg^{-1}. Similarly, a long-term experiment at Broadbalk of England showed that the critical value of Olsen P leaching loss was 60 mg kg^{-1} [7].

The application of P in excess of plant requirements can lead to a buildup of P in soil, saturation of P sorption sites and thus lead to P desorption into soil solution and loss by leaching[8], likely as particulate or colloidal P[9,10]. McDowell and Sharpley[11] reported that the proportion of reactive P in farmland which is transferred through soil by leaching is higher than through surface runoff. Many studies[12,13] have shown that the amount of P lost by leaching is equivalent to or greater than the amount lost by surface-runoff and soil erosion.

Scientists in China and around the world are now paying increasing attention to P losses due to the increasing occurrence and severity of eutrophic algal blooms[14,15]. The migration of P from soil is one of major area of research in China[15-20].

However, such research has mainly been conducted in high rainfall regions such as the Southern lake area and the paddy soils area. There is very limited information on phosphate leaching resulting from fertilization of salt-affected soil. Many salt-affected soils, which were abandoned in the early 1980's due to drought, waterlogging, alkalization, salinization and desertification in the lowland of North China Plain, have been reclaimed successfully[21]. These soils are an important land resource located in regions where abundant sunlight and heat are available therefore have great potential for developing productive agriculture.

The primary objective of this study, which was run for 24 years, from 1983 until 2007, was to investigate the effects of long-term fertilization practices on phosphate leaching in a salt-affected soil so that practical advice on phosphorous fertilizer applications could be provided to farmers. Results from this long-term study have implications for P accumulation and loss in salt-affected soils around the globe where saline soils are present.

MATERIALS AND METHODS

Study site: The experimental plots were located at the Quzhou Experimental Station in Quzhou County (114°50' 22.3″-115°13′27.4″ E 36°34′ 43″-36°57′56″ N), 36 m a.s.l., in Hebei Province, China. The climate in the region is warm-temperate-monsoon with an annual average rainfall of 542.8 mm and annual average top-soil temperature of 13.1°C. The distribution of the rainfall is: 11.8% in spring (March-May), 65.5% in summer (June-August), 19.5% in autumn (September-November) and 3.2% in winter (December-January).

Previous studies[22-24] showed that rapidly available phosphorous levels were in the range of 0-1.0 mg kg^{-1}, in salt wastelands in the 1970's.

The soil in the experimental site was classified as Endorusti-Ustic Cambosols[25]. The topsoil (0-20 cm) is light loam and the subsoil (20-40 cm) is sandy loam. Soil properties are given in Table 1.

Experimental design: The experiment began in 1983. The treatments were allocated to plots (11×4 m) in a complete randomized block design with 9 treatments and 3 replicates. Cement borders (50×5 cm) were built around the plots to prevent water and nutrients lateral seepage. Experimental treatments included CK, N_1, N_2, P_1, P_2, N_1P_1, N_1P_2, N_2P_1, N_2P_2 , where CK represents the control, N_1 and N_2 are application of nitrogen fertilizer at rate of 270 and 540 kg N ha^{-1} year^{-1}, respectively; and P_1 and P_2 are application of phosphorous fertilizer at rate of 67.5 and 135 kg P_2O_5 ha^{-1} year^{-1},

Table 1: Soil properties of experimental area

Layer (cm)	pH value	Total salts (g kg^{-1})	SOM (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	AN (mg kg^{-1})	RP (mg kg^{-1})	RK (mg kg^{-1})
0-20	7.80	1.02	7.00	0.37	0.60	50.60	9.94	92.60
20-40	7.80	1.11	4.00	0.22	0.52	36.40	3.20	71.30

SOM: Content of soil organic matter, TN: Total nitrogen concentration in the soil, TP: Total phosphorus concentration in the soil, AN: Available nitrogen concentration in the soil, RP: Concentration of the rapidly available phosphorus in the soil, RK: Concentration of the rapidly available potassium in the soil

Table 2: Varieties of wheat and maize used in the study

Years	Wheat (*Triticum aestivum* L.)	Maize (*Zea mays* L.)
1984-1989	Taishan 1	Yedan 3
1990-1994	Jimai 23	Yedan 13
1995-2000	Han 4564	Xiyu 3
2001-2007	Han 6172	Zhengdan 958

Table 3: Range of total P and reactive P values in the control plots

	1983		2007	
Soil depth (cm)	Total P ($g\ kg^{-1}$)	Reactive P ($mg\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Reactive P ($mg\ kg^{-1}$)
0-20	0.60	9.94	0.54	6.40-8.60
20-40	0.52	3.20	0.50-0.47	4.00-4.50
40-60	-	-	0.40-0.44	7.77-8.66
60-100	-	-	0.37-0.42	7.25-8.33

respectively. Two crops (including four varieties of wheat and four varieties of maize) were planted each year: winter wheat (*Triticum aestivum* L.) from earlier October to the 1st week of June and maize (*Zea mays* L.) from the second week of June to the end of September throughout the study period (Table 2). Two fields were set aside as control after the saline soil had been remediated in 1983: one field was a highland with an overlapping land cover having 5% shrubs and 75% herbaceous plants; another was an overlapping land cover with 75% of arbor, 1% shrub, 35% is an herbaceous layer in 2009.

The N fertilizer was urea (46% N) and the P fertilizer was triple super-phosphate (43% P_2O_5), which were applied in the 0-20 cm layer. For winter wheat, 30% of the total fertilizer N was applied at the time of planting in early October and the another 20% was spread on the soil surface in April, followed by surface irrigation. For maize, 30 and 20% of the N fertilizer was applied at sowing and at 10-12 leaf stage, respectively. The P fertilizer was applied only to winter wheat annually at crop seeding. Generally, each crop was irrigated 3-4 times (705-825 $m^3\ ha^{-1}$ each time) with ground water. Salt content of the ground water was about 0.75 $g\ L^{-1}$.

Soil samples were collected from 0-20, 20-40, 40-60 and 60-100 cm depths after the harvest of maize in October 2007. The samples were air-dried and passed through a 0.149 mm sieve for determination of total phosphorus content. The samples were passed through a 2.0 mm sieve for determination of RP content.

Total phosphorus concentration was measured using the molybdate blue colorimetric method after the soil samples were digested in $HClO_4+H_2SO_4$ acids. The concentration of reactive phosphorus was also determined by using the molybdate blue colorimetric method, following extraction of soil samples with 0.5 $mol\ L^{-1}$ $NaHCO_3$. Experimental data were analyzed by ANOVA (analysis of variance) and the LSD multiple range tests[26].

RESULTS AND DISCUSSION

Phosphorus change in control plots: In control plots, the concentrations of soil total P decreased slightly from 0.60 $g\ kg^{-1}$ in 0-20 cm layer and 0.52 $g\ kg^{-1}$ in 20-40 cm layer in 1983 to 0.54 $g\ kg^{-1}$ and 0.47-0.50 $g\ kg^{-1}$ in 2007, respectively. Along the vertical soil profile, total P concentrations also exhibited a decreasing trend from 0-20 to 60-100 cm layer in 2007 (Table 3). The levels of reactive P increased from 0.5-1.0 $mg\ kg^{-1}$ in 1970 to 6.40-8.60 $mg\ kg^{-1}$ in the 0-20 cm layer in 2007. In addition, the PR levels were higher in the 0-20, 40-60 and 60-100 cm layers compared to in the 20-40 cm layer (Table 3), an indication that the roots of the herbaceous plants absorbed phosphorus mainly from the 20-40 cm layer.

Effects of N and P applications on total P: In the surface layer (0-20 cm), total P contents in treatments with continuous application of P fertilizer from 1983 to 2007 increased from 0.60 $g\ kg^{-1}$ in 1983 to 0.64-0.96 $g\ kg^{-1}$ in 2007 and the rate of increase was 6.67-60%. In the subsurface layer (20-40 cm), total P content changed from 0.52 $g\ kg^{-1}$ in 1983 to 0.46-0.60 $g\ kg^{-1}$ in 2007 and the rate of change was 1.54-15.38% (Table 1, Fig. 1).

The total P level was significantly higher ($p<0.05$) in the P_2, N_2P_2 and N_1P_2 treatments and ranged from 0.94-0.96 $g\ kg^{-1}$ in 0-20 cm layer (Fig. 1) and the rate of accumulation reached 16.3-17.1 $mg\ kg^{-1}\ year^{-1}$ from 1983 to 2007. The total P concentration in N_2P_2 (0.60 $g\ kg^{-1}$) in the subsurface layer (20-40 cm layer) was significantly higher than other treatments (0.42-0.53 $g\ kg^{-1}$) ($p<0.05$) but there were no significant differences in total P levels in all other treatments or the control in this layer. The total P concentration in all treatments ranged between 0.41-0.55 $g\ kg^{-1}$ in the 40-60 cm layer and from 0.43-0.51 $g\ kg^{-1}$ in the 60-100 cm layer, but there was no significant difference between the treatments ($p>0.05$).

Effects of N and P applications on reactive P leaching: In the surface layer (0-20 cm), the rapidly available phosphorus contents in treatments with continuous application of P fertilizer increased from 9.94 $mg\ kg^{-1}$ in 1983 to 15.56-43.24 $mg\ kg^{-1}$ in 2007 and the rate of increase was 56.53-335.01%. In the subsurface layer (20-40 cm), reactive P changed from 3.20 $mg\ kg^{-1}$ in 1983 to 6.68-15.03 $mg\ kg^{-1}$ in 2007 and the rate of change was 108.75-369.69% (Table 1, Fig. 2).

The application of P fertilizer resulted in significantly higher ($p<0.05$) levels of reactive P in the surface layer (0-20 cm) in the P_2, N_1P_2 and N_2P_2 treatments (Fig. 2). There was also a significant difference in the reactive P

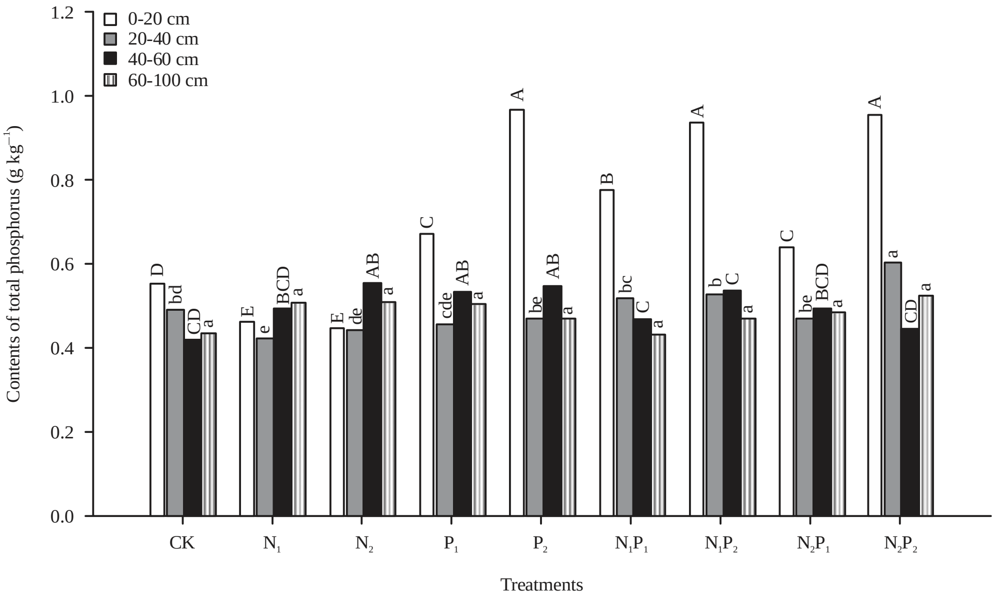

Fig. 1: Influence of fertilization on contents of total P in the soil in 2007. CK: No fertilizer; N_1: 270 kg N ha^{-1} year^{-1}, N_2: 540 kg N ha^{-1} year^{-1}, P_1: 67.5 kg P_2O_5 ha^{-1} year^{-1}, P_2: 135 kg P_2O_5 ha^{-1} year^{-1}, respectively

Bars with the same uppercase letter(s) and lowercase letter(s) indicate no significant difference at $p<0.05$ in the 0-20, 20-40, 40-60 and 60-100 cm layers

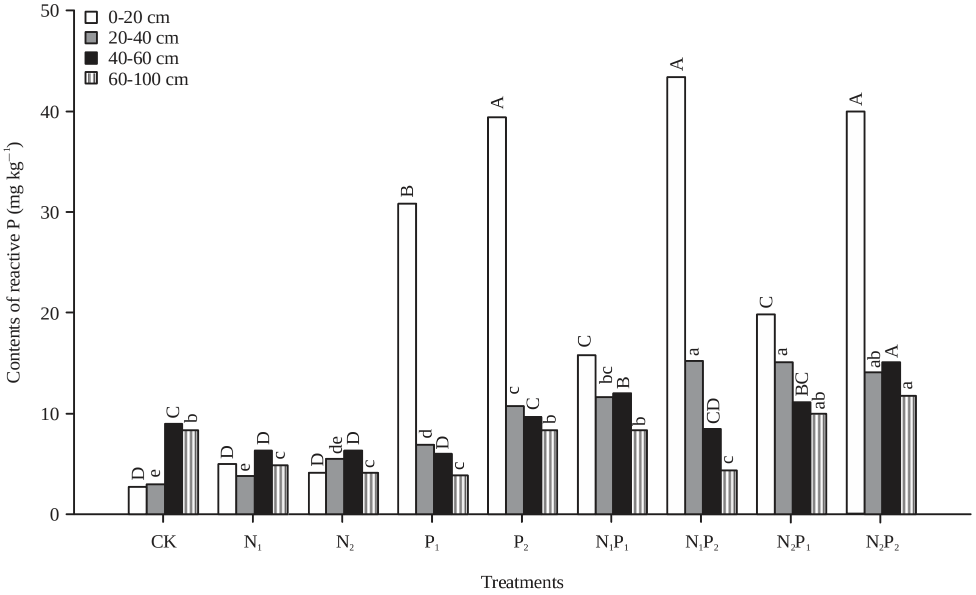

Fig. 2: Influence of fertilization on contents of reactive P in the soil in 2007. CK: No fertilizer, N_1 and N_2: 270 and 540 kg N ha^{-1} year^{-1}, respectively, P_1 and P_2: 67.5 and 135 kg P_2O_5 ha^{-1} year^{-1}, respectively

Bars with the same uppercase letter(s) and lowercase letter(s) indicate no significant difference at $p<0.05$ in the 0-20, 20-40, 40-60 and 60-100 cm layers

level ($p<0.05$) between the N_1P_1 treatment and the N_2P_1 and the P_1 treatments in the surface layer, with lower reactive P in the N_1P_1 treatment. However, this trend was not observed at the lower layers.

Table 4: Amount of phosphorus uptake by crop

Treatments	CK	N_1	N_2	P_1	P_2	N_1P_1	N_1P_2	N_2P_1	N_2P_2
	$(kg\ ha^{-1}\ year^{-1})$								
Wheat	12.09^{de}	11.54^{e}	12.85^{cde}	19.73^{c}	19.50^{cd}	54.31^{b}	55.85^{b}	$56.34a^{b}$	63.61^{a}
Maize	22.37^{C}	27.75^{BC}	28.08^{BC}	30.24^{B}	30.57^{B}	55.34^{A}	55.70^{A}	57.54^{A}	60.35^{A}
Wheat+maize	34.46	39.29	40.93	49.97	50.07	109.65	111.55	113.88	123.96
Amount of P fertilizer	0.00	0.00	0.00	67.50	135.00	67.50	135.00	67.50	135.00
Balance of soil P	-34.46	-39.29	-40.93	17.53	84.93	-42.15	23.45	-46.38	11.04

CK: No fertilizing fertilizer, N_1 and N_2: Fertilizing 270 and 540 kg N ha^{-1} $year^{-1}$, respectively, P_1 and P_2: Fertilizing 67.5 and 135 kg P_2O_5 ha^{-1} $year^{-1}$, respectively. Columns with the same uppercase letter(s) and lowercase letter(s) indicate no significant difference at $p<0.05$. The amount of phosphorus up taken by crop was accumulated using the average yield of wheat and maize from 1984-2007 and for every 100 kg yield formation needs the amount of P_2O_5

At the subsurface layer (20-40 cm), there were no significant differences ($p>0.05$) between the P_2, N_1P_1, N_1P_2, N_2P_1 and N_2P_2 treatments and no significant differences ($p>0.05$) between the P_1, N_1 and N_2 treatments and the control.

At the 40-60 cm layer, the N_2P_2 treatment had significantly higher reactive P ($p<0.05$) than all other treatments. There were no significant differences in reactive P levels between all other treatments and the control.

At the 60-100 cm layer, there was no significant difference in reactive P levels between the P_2, N_1P_1, N_2P_1 and N_2P_2 treatments and the control. Notably, the level of reactive P in the N_1P_2 treatment was not significantly different from the N_1, N_2 and P_1 treatments.

Phosphorus uptake by crop: Under long-term fertilizer application, the amount of P taken up by wheat and maize from the soil increased. Specifically, the amount of P taken up by wheat in the N_2P_2 treatment reached 63.61 kg ha^{-1} $year^{-1}$ and was significantly higher than in the other treatments ($p<0.05$), with the exception of the N_2P_1 treatment (Table 4). The amount of P taken up by wheat in N_1P_1, N_1P_2 treatments (54.31-55.85 kg ha^{-1} $year^{-1}$) was significantly higher than the CK, N_1, N_2, P_1, P_2 treatments (11.54-19.73 kg ha^{-1} $year^{-1}$) ($p<0.05$) and the amount in the P_1 treatment (19.73 kg ha^{-1} $year^{-1}$) was higher than the CK, N_1 and N_2 treatments (11.54-12.85 kg ha^{-1} $year^{-1}$) ($p<0.05$) with the exception of the P_2 treatment. Similarly, the amount of P taken up by maize in the N_2P_2, N_2P_1, N_1P_2, N_1P_1 treatments reached 60.35, 57.54, 55.70, 55.34 kg ha^{-1} $year^{-1}$, respectively and were significantly higher than the CK, N_1, N_2, P_1, P_2 treatments (22.37-30.57 kg ha^{-1} $year^{-1}$) ($p<0.05$) and the amount in the P_2 and P_1 treatments (30.57 and 30.24 kg ha^{-1} $year^{-1}$) were significantly higher than the CK (22.37 kg ha^{-1} $year^{-1}$) ($p<0.05$).

Additional analysis showed that the treatments of simultaneous application of P and N fertilizers (N_1P_1, N_1P_2, N_2P_1 and N_2P_2) had greater P uptake amounts of 109.65-123.96 kg P_2O_5 ha^{-1} $year^{-1}$ by wheat and maize. These values were higher than the treatments of applying N fertilizer or P fertilizer alone (CK, N_1 ,N_2, P_1 and P_2). Furthermore, P uptake was higher in the treatments of applying P fertilizer alone (P_1, P_2) than in the treatments with no P application (N_1, N_2 and CK) and was higher in the treatments of applying N fertilizer alone than the CK treatment (Table 4).

Taking into account both the amount of applied P fertilizer and the amount of P taken up by wheat and maize, it was found that soil P content in the treatments of no P application (e.g., CK, N_1 and N_2) decreased to 34.46-40.93 kg ha^{-1} $year^{-1}$ whereas in the treatment with P application alone (e.g., P_1, P_2) it increased to 17.53, 84.93 kg ha^{-1} $year^{-1}$. Furthermore, the content of soil P in the treatments with lower P application rate of P_1 and N application (e.g., N_1P_1 and N_2P_1) decreased to 42.15, 46.38 kg ha^{-1} yr^{-1} while at the higher P application rate of P_2 and N fertilizer (e.g., N_1P_2 and N_2P_2) soil P increased to 23.45, 11.04 kg ha^{-1} $year^{-1}$.

Results given show that the amount of P absorbed by wheat and maize were greater than the amount of P applied in the treatments of N_1P_1 and N_2P_1. In other words, the applied P fertilizer could not fulfill the requirement of crop growth and, as a result, the crop needed to take up P from the soil reserve and thereby to exhaust the soil P reserve. On the other hand, the amount of applied P fertilizer at P_2 exceeded the requirement of crop growth therefore the content of soil P increased in the treatments of N_1P_2, N_2P_2.

Correlation between soil salinity and P content: The changes observed on total P and reactive P levels in the control plots from the 1970's to 2007 are likely correlated to changes in the salinity level in those plots. As salt concentration increased to 6-10 g kg^{-1}, the reactive P concentrations decreased from 2.0-3.0-0.5-1.0 mg kg^{-1}, even to zero in the salt wasteland in 0-20 cm layer in 1970's. At high soil salt level, calcium ions (Ca^{2+}) from the dissolution of calcium compounds such as gypsum ($CaSO_4.2H_2O$) and calcium chloride hexahydrate ($CaCl_2.6H_2O$), which have higher solubility than calcium carbonate ($CaCO_3$), formed precipitates with P therefore reduced P availability in the reactive P form[23]. Remediation and management strategies including consolidation of farmland and extraction of salt water and replenishment with

Table 5: Contents of total salt and the salt ions between the experimental plots and farmland

Parameters	HCO_3^- (g kg^{-1})	Cl^- (g kg^{-1})	SO_4^{2-} (g kg^{-1})	Ca^{2+} (g kg^{-1})	Mg^{2+} (g kg^{-1})	K^++Na^+ (g kg^{-1})	Total salt (g kg^{-1})
Experimental plots	0.27	0.19	0.29	0.08	0.03	0.21	1.06
Farmland	0.28	0.18	0.44	0.11	0.04	0.30	1.21

freshwater (e.g., proper irrigation and drainage management) effectively reduced salinity to 1.02 g kg^{-1} in the soil in 1983[23]. As a result, the levels of total salt and salt ions in the experimental field were lower than the average values measured for Quzhou County (with the exception of Cl^-) (Table 5). Reduced salinity accelerated the transformation of TP to RP, led to the observed increased RP levels in 2007. Furthermore, natural vegetation improved cycling of P in the soil and promoted release of total P in the natural salt-vegetation restoration area, where the control plots were located and resulted in decreased levels of total P and reactive P in the soil over the duration of the experiment. Overall, the vegetation was not able to obtain enough nutrients for its normal growth in the control plots, so plant roots grew slowly and the amount of roots was small.

Soil residual P content: The total P level in the control was measured to be 0.54 g kg^{-1} in the 0-20 cm layer in this study. Interestingly, similar values have been reported by others based on their long-term experiments. For example, the value was 0.58 g kg^{-1} in the Rothamsted experimental station with continuous wheat cropping for 101 years (1843-1944); 0.42 g kg^{-1} in Saxmundham with rotating cropping for 57 years (1899-1956) and 0.55-0.57 g kg^{-1} in Hoosfield with continuous barley cropping for 93 years (1882-1975)[27]. These data suggest that total P levels tend to stabilize at 0.40-0.60 g kg^{-1} range in surface soil layer with natural vegetation or field crops absorbing P without application of any fertilizers, regardless of location.

Leaching loss of P: In the absence of P fertilizer application, N fertilizer promoted the releasing of P in the 0-20 and 20-40 cm layers, in which N could increase P solubility and availability[28]. Accumulation of P in these soils was a result of P fertilizer application and higher the fertilizer application rate, higher the total P accumulation rate in the surface soil layer. The significant P accumulation in soil profiles could partially or completely saturate P sorption sites in soils[29,30] resulting in P loss through leaching. Leaching losses increased with increased amount of P applied. Phosphorous leaching from cultivated soil can contaminate groundwater and this risk increases as the degree of soil P saturation increases through common agricultural activities[31,32]. The observation that P can be lost through leaching to subsurface layers in warm-temperate monsoon climate on the North China plain is in contrast to the earlier belief that P diffusion from fertilizer seldom exceeded 3-5 cm below the surface layer[33]. The results of 24 years experiment clearly demonstrated that long-term application of P fertilizer resulted in P accumulation in the 0-100 cm soil layer and leaching of P from surface layer to subsurface layers (60-100 cm). The extent of P accumulation and leaching was affected by both P application rate as well as N/P ratio.

CONCLUSION

In this study, it was showed that total P content decreased rapidly and reached a constant level of 0.40-0.60 g kg^{-1} during the 24 years experimental period in the reserved control plot and in the field of intensive agricultural production without application of fertilizer. The content of reactive P increased significantly from 0.5-1.0 mg kg^{-1} in the 1970's to 6.40-8.60 mg kg^{-1} in 2007 in the reserved control plot. In the long-term experimental field, the content of total P and reactive P increased to 0.96 g kg^{-1} and 43.24 mg kg^{-1}, respectively, with continuous application of P fertilizer in the surface layer. The accumulation of reactive P led to P loss from surface layer to subsurface layer, even to 40-100 cm layer in the area of warm-temperate monsoon climate for 24 years and the amount of accumulation and P loss increased with increasing rate of P application and N/P ratio.

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