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Impacts of fertilizer application rates on phosphorus dynamics in salt-affected soil

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ABSTRACT

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As a new rebuilding agricultural soil on the North China plains, the salt-affected soil had a short soil-forming process of about 30 years. This paper describes the effect of different fertilization systems on phosphorus (P) dynamics in saline-alkali uncultivated land, in the reserved natural salt-vegetation back zone, and in different phases of fertilization for 24 years on the North China plains. The treatments included control (or check, CK), N_1, N_2, P_1, P_2, N_1P_1, N_1P_2, N_2P_1, N_2P_2. The contents of total phosphorus (TP) showed a significantly decreasing trend from 1.32–1.38 g P/kg to 0.40–0.96 g P/kg. The contents of rapidly available P (RP) were low in the no-P fertilizer treatments and the RP concentrations increased with P fertilizer applications. Corn was the crop that used the most P, especially in the no-P and P fertilizer-only treatments. The treatment with 270 kg N/ha/year and 59 kg P/ha/year represents the most economical fertilizer rates for these salt-affected soils on the North China plains.

Keywords: agricultural management; macronutrient; long-term experiment; phosphorus balance; yield

Phosphorus (P) is one of the macro-elements essential for plant growth. In 1957, J.E. Russell, the famous pedologist in England, described that soil P is in a non-water-soluble form, it always stays in the surface soil. As P fertilizers are usually applied to the top layer, subsoil layers often have low P concentrations, thus having enormous capacity to absorb P. Therefore, it is often believed that P is unlikely to leach through the plough layer to subsoil layers and to leach through to groundwater (Gburek et al. 2000). As a consequence, fertilizer P applications have increased over the years, gradually resulting in the accumulation of P in the soil. The long-term application of fertilizers can, however, lead to P accumulation in surface horizons greater than that required for optimum plant growth, thus increasing the potential for P loss to surface waters, leading to eutrophication (McDowell et al. 2001).

Saline soils are widely distributed and are an important land resource for agriculture. Soil salinization is one of the factors of soil degradation in the world (Qureshi et al. 2008). In the early 1970's, large areas of the salt-affected soils on the lowlands of the North China plains were reclaimed successfully by using fresh water from deep wells for irrigation and by deepening the drainage ditches to lower the groundwater table. However, even after the salt problem was removed, crops still did not grow well because of low organic matter and deficiencies of nitrogen and phosphorus in these reclaimed soils. Soil fertility management was thus essential for improving crop yield. Niu et al. (2005, 2011) found that the amounts of soil total P (TP) and rapidly available P (RP) increased significantly with P fertilizer applications from 1984 to 2001 in the salt-affected soils. There is a lack of knowledge on P dynamics in these salt-affected

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soils as affected by different rates of nitrogen (N) and P fertilizers applied over a long-term. This knowledge is important for developing optimum fertilizer application rates. This paper reports P dynamics in a saline-alkali uncultivated land, and discusses the influence of different N and P fertilizer treatments and agricultural management practices on the accumulation of soil P in a new rebuilding agricultural soil on the North China plains.

Table 1. Cultivars of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) used in the study

Year	Wheat	Maize
1984–1989	Taishan 1	Yedan 3
1990–1994	Jimai 23	Yedan 13
1995–2000	Han 4564	Xiyu 3
2001–2007	Han 6172	Zhengdan958

MATERIAL AND METHODS

Study site. The experimental plot is located in the east of the Quzhou Experimental Station in Quzhou county (115°00'E, 36°52'N, 36 m a.s.l.), Hebei, China. The climate at the site is warm-temperate monsoonal climate with an annual average rainfall of 542.8 mm and annual topsoil temperature of 13.1°C. The soil is classified as Typic Ustochrepts. The topsoil (0–20 cm) was light loam and subsoil (20–40 cm) was sandy loam.

Experimental design. The experiment was started in 1983. The treatments were allocated to plots (11 × 4 m) in a randomized complete block design with 9 treatments and 3 replicates. The treatments included control (or check, CK), N_1, N_2, P_1, P_2, N_1P_1, N_1P_2, N_2P_1, N_2P_2, in which N_1, N_2 means 270 and 540 kg N/ha/year, respectively; P_1, P_2 means 29.5 and 59 kg P/ha/year, respectively. The N fertilizer applied was urea (46% N) and P fertilizer was triple superphosphate (18.79% P). Two crops were rotated each year: wheat (*Triticum* L.) and maize (*Zea mays* L.). The wheat and maize cultivars used for this study are shown in Table 1. Some soil properties are shown in Table 2.

Soil samples were collected from 0–20 cm and 20–40 cm depths in June after the harvest of wheat, and in October after the harvest of maize every year. The samples were air-dried, and passed through a 0.25 mm sieve for determination of TP. The soil was passed through a 1 mm sieve for determination of RP.

The TP was measured using molybdate blue colorimetric method, after the soil samples were digested in $HClO_4$ + H_2SO_4 acids. RP in soil was measured using molybdate blue colorimetric method, following the extraction with 0.5 mol/L $NaHCO_3$. Experimental data were analysed by ANOVA, and the least significant difference (*LSD*) multiple range tests were performed.

RESULTS AND DISCUSSION

P dynamics in saline-alkali uncultivated land. During the initial stages of salinity remediation in 1973, this region was low-lying with poor drainage, and the groundwater was 1–1.5 m below ground in the rainy season. The groundwater was salt water with salt concentrations ranging between 5–7 g/L, and sometimes reaching 11–16 g/L. In this arid climate, evapotranspiration (1840.6 mm) is far greater than precipitation (603.8 mm in 1963–1977) and this leads to the accumulation of salt in the soil, forming salt-affected soils, leading to a barren waste land. The soil organic matter (SOM) content was low with 2–5 g/kg, and the RP content was 2–3 mg/kg, or zero (Xin and Li 1990).

Table 2. Some properties of the soil used in the study (1983)

Layer (cm)	pH_{H_2O}	Total salts	SOC	TN	TP (P)	AN	RP (P)	RK (K)
		(g/kg)				(mg/kg)		
0–20	7.8	1.02	4.06	0.37	0.60	50.60	9.94	92.60
20–40	7.8	1.11	2.32	0.22	0.52	36.40	3.20	71.30

SOC – soil organic carbon; TN – total nitrogen; TP – total phosphorus; AN – ammonium nitrogen; RP – rapidly availg able phosphorus; RK – available potassium

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Table 3. The changes of total phosphorus (TP) and rapidly available phosphorus (RP) in the saline-alkali uncultivated land

	1973	1983	1985		2007	
	0–20 cm		0–20 cm	20–40 cm	0–20 cm	20–40 cm
TP (g/kg)	–	–	1.37	1.18	0.54*, 0.54+	0.47*, 0.50+
RP (mg/kg)	2–3; 0.5–1	4.3	9.94	3.20	6.40*, 8.60+	4.00*, 4.50+

*means the reserved saline-alkali uncultivated land, the shrub cover was 5% and a herbaceous layer was 75%; +means the reserved natural salt-vegetation back zone, the cover of trees was 75%, 1% was a shrub layer and 35% was a herbaceous layer. The investigation time was October 9, 2009

In order to overcome the problems of drought, waterlogging, alkalization, salinization and desertification on the North China plains, a number of engineering measures were taken to improve the soil physicochemical properties. In 1985, the TP and RP contents were recorded as 1.37 g/kg and 9.94 mg/kg in the 0–20 cm layer. Because of soil P removal by rainfall (Koopmans et al. 2001, Elliott et al. 2002), the contents of TP and RP in the reserved saline-alkali uncultivated land decreased to 0.54 g/kg and 6.40 mg/kg in 0–20 cm layer in 2007 (Table 3). For comparison purposes, the content of TP in the no-fertilizer plots was 0.58 g/kg in the Rothamsted experimental station with continuous wheat cropping for 101 years (1843–1944) (Shen 1984). The results from this study showed that the contents of TP in the soil changed from 0.40 to 0.60 g/kg under the long-term experimental conditions for over 30 years. From this, it can be seen that the soil TP and RP reduced persistently in the non-fertilized plots (Xu et al. 2015).

The effect of nitrogen fertilizer on soil P dynamics

Effect on soil total P. Figure 1 shows that after 24 years, TP decreased significantly. The content of TP in CK, N_1 and N_2 treatments decreased from 1.32–1.35 g/kg in 1985 to 0.45–0.55 g/kg in 0–20 cm layer in 2007. These results support the reports from other long-term studies, which also showed similar decreasing trends in TP in no-fertilizer and N fertilizer-only treatments (Yang et al. 2007). When P fertilizer was applied, the TP contents also decreased when N fertilizer was applied. For example, the TP contents in the N_1P_1 and N_2P_1 treatments both decreased by 57.7% and 61.5% (20–40 cm layer), respectively; the TP contents in the N_1P_2 and N_2P_2 treatments decreased by 56.9% and 50.8% (20–40 cm layer), respectively. The decrease was greater with higher N fertilizer application rates, indicating higher P uptake and removal at higher N rates, the results indicated

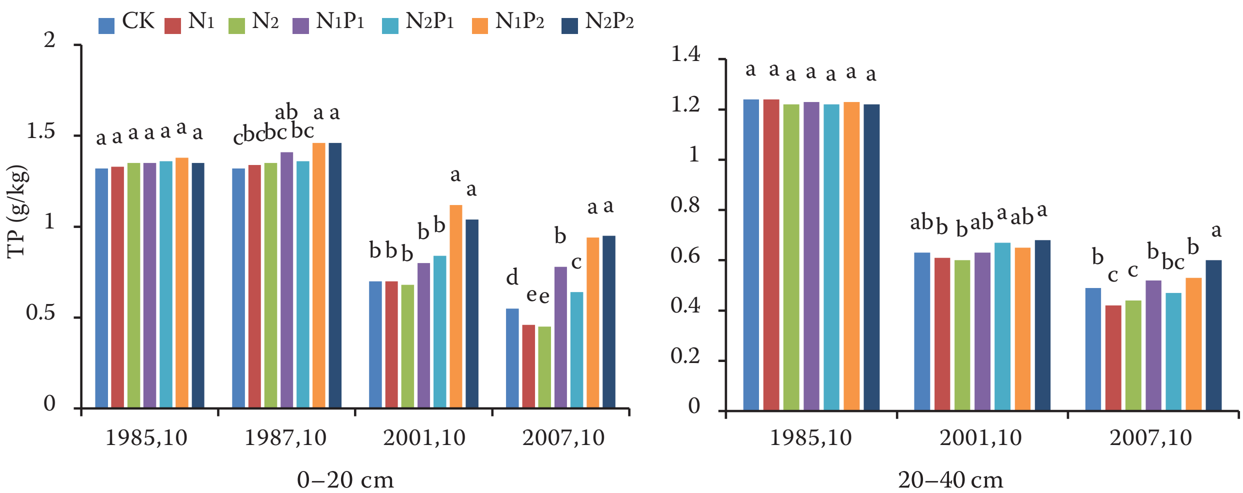

Figure 1. The effect of nitrogen (N) fertilizer on total phosphorus (TP) dynamics in the soil. CK – control; N_1 – 270, N_2 – 540 kg N/ha/year; P_1 – 29.5, P_2 – 59 kg P/ha/year. Small letters indicate significant difference at $P < 0.05$

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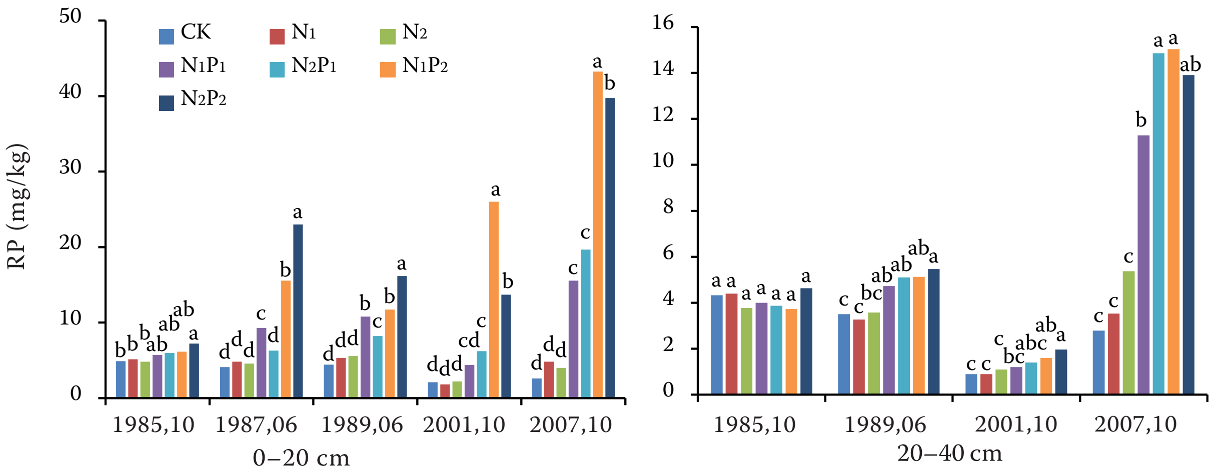

Figure 2. The effect of nitrogen (N) fertilizer on rapidly available phosphorus (RP) dynamics in the soil. CK – control; N_1 – 270, N_2 – 540 kgN/ha/year; P_1 – 29.5, P_2 – 59 kg P/ha/year. Small letters indicate significant difference at P < 0.05

that the decrease of TP in the soil was the result of synergism of NH_4^+ and $H_2PO_4^-$ in the body of wheat and corn, which absorbed P from the soil.

Effect on rapidly available P. Figure 2 shows that the content of RP in the soil changed from 4.3 mg/kg in 1983 to 4.83–7.20 mg/kg in the 0–20 cm layer in 1985, thus indicating an upward trend as a result of improving the environmental and soil conditions, and continued P fertilizer inputs (Huang et al. 2006, Qu et al. 2009). The contents of RP in the CK, N_1, N_2 treatments changed from about 5.00 mg/kg in 1985 to 2.60–4.80 mg/kg in the 0–20 cm layer and 2.79–5.37 mg/kg in 20–40 cm layer in 2007. The result indicated that the contents of RP were kept in the lower level in the long-term experimental plots. In contrast, the RP in the N_1P_1, N_2P_1 treatments increased from 5.70, 5.97 mg/kg (0–20 cm layer), and 3.87, 4.00 mg/kg (20–40 cm layer) in 1985 to 15.56, 19.66 mg/kg and 11.29, 14.86 mg/kg in 2007, respectively. Obviously, the RP in the N_1P_2, N_2P_2 treatments also increased from 1985 to 2007. These results show that RP can be increased by higher rates of P fertilizer application in these soils.

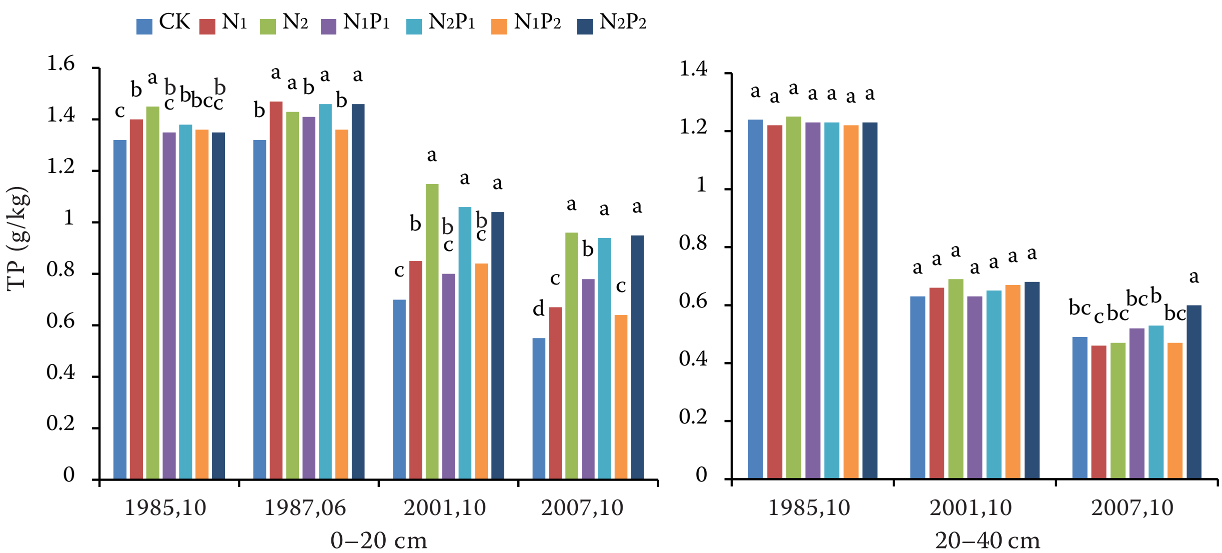

Figure 3. The effect of phosphorus (P) fertilizer on total phosphorus (TP) dynamics in the soil (g/kg). CK – control; N_1 – 270, N_2 – 540 kg N/ha/year; P_1 – 29.5, P_2 – 59 kg P/ha/year. Small letters indicate significant difference at P < 0.05

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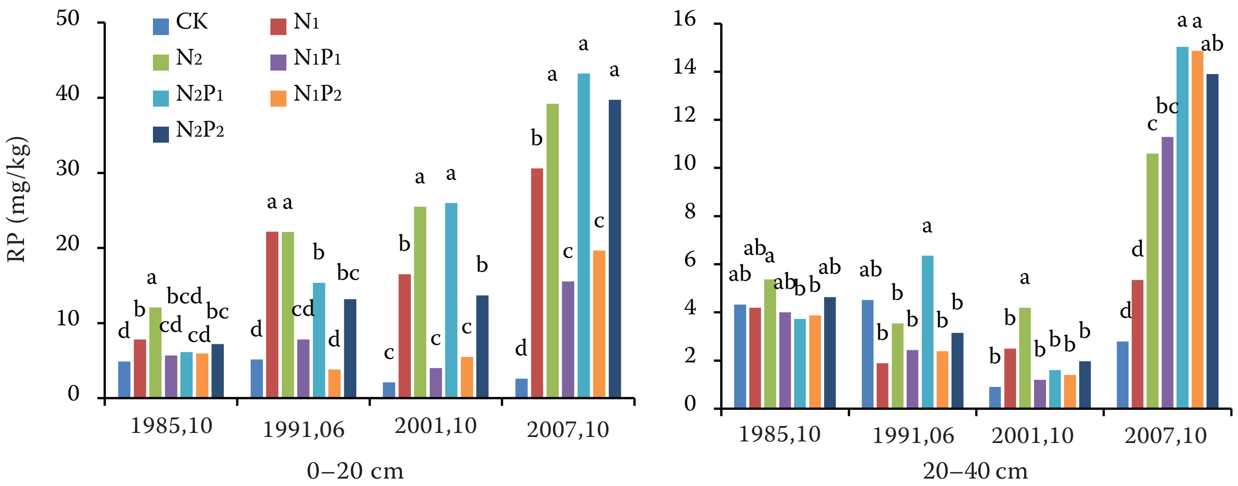

Figure 4. The effect of phosphorus (P) fertilizer on rapidly available phosphorus (RP) dynamics in the soil (mg/kg). CK – control; N_1 – 270, N_2 – 540 kg N/ha/year; P_1 – 29.5, P_2 – 59 kg P/ha/year. Small letters indicate significant difference at $P < 0.05$

The effect of P fertilizer on soil P dynamics

Effect on TP dynamics (Figure 3). In 1985, the TP in the P_2 treatment (1.45 g/kg) was higher than in the other treatments in the 0–20 cm layer ($P <$ 0.05). From June 1987, the TP in every treatment decreased, changing from 0.70 to 1.15 g/kg in the 0–20 cm layer in 2001. TP in P_2, N_1P_2 and N_2P_2 was higher than in the other treatments ($P < 0.05$).

In 2007, TP in the soil decreased further, changing from 0.55 to 0.96 g/kg. TP in the P_2, N_2P_2 and N_1P_2 treatments was higher than in the other treatments ($P < 0.05$). In the 20–40 cm layer, TP changed from 0.46 to 0.60 g/kg, and TP in the N_2P_2 treatment was higher than in the other treatments ($P < 0.05$) and TP in the N_1P_2 treatment was higher than in the P_1 treatment ($P < 0.05$).

These decreases in the P_1 and P_2 treatments were equivalent to 52.1% and 62.3% in the 0–20 cm layer and 33.8% and 62.4% in the 20–40 cm layer, respectively. In the N_1P_1 and N_1P_2 treatments, the decreases were equivalent to 42.2, 31.9% in the 0–20 cm layer, and 57.7, 56.9% in the 20–40 cm layer, respectively. In the N_2P_1 and N_2P_2 treatments the decreases were equivalent to 52.9% and 29.6% and 61.5% and 51.2%, respectively. These results showed that the content of TP in the soil was further influenced by agricultural management in addition to P fertilization applications.

The effect of P fertilizer on RP in the soil (Figure 4). The content of RP in all treatments changed from 4.3 mg/kg in the 0–20 cm layer in 1983 to 4.90–12.10 mg/kg in 1985, where the content of RP in the P_2 treatment (12.10 mg/kg) was higher than in all the other treatments ($P < 0.05$); it changed to 4.20–5.37 mg/kg in 20–40 cm layer and it was higher in the P_2 treatment than in the N_2P_1 and N_1P_2 treatments ($P < 0.05$).

In 1991, the content of RP changed from 3.81 to 22.17 mg/kg in the 0–20 cm layer. The contents of RP in the P_1 and P_2 treatments were higher than in the other treatments ($P < 0.05$). In the 20–40 cm layer, the content of RP was higher in the N_1P_2 treatment than in the other treatments ($P < 0.05$), except the CK treatment.

In 2001, the RP concentrations in every treatment differed significantly, ranging from 2.10 to 26.00 mg/kg in the 0–20 cm layer, and the concentrations in the CK, N_1P_1 and N_2P_1 treatments further decreased to a critical value similar to that in the saline-alkali uncultivated land. RP concentrations in the N_1P_2, P_2, P_1 and N_2P_2 treatments increased. In the 20–40 cm layer, RP concentrations in all the treatments were the lowest.

In 2007, 24 years after the experiment begun, the RP concentrations increased from 15.56 to 43.24 mg/kg in the 0–20 cm layer, and from 5.35 to 15.03 mg/kg in the 20–40 cm layer with P fertilizer application. The concentrations of RP in the N_1P_2 and N_2P_1 treatments were higher than in the other treatments ($P < 0.05$), except the N_2P_2 treatment in the 20–40 cm layer. This indicates that the amount of P fertilizer applied was in excess of that required by plants.

In conclusion, the results demonstrated that the RP concentrations were increased with P ferti-

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Table 4. The average yield of crops and the phosphorus (P) balance in the soil (kg/ha/year)

Treatment	Average yield		Total yield	Amount of P taken away			Applied P fertilizer	P balance
	wheat	corn		wheat	corn	total		
CK	967.20	2601.13	3568.33	12.09	31.21	43.30	0	–43.30
N_1	923.44	3226.99	4150.43	11.54	38.72	50.26	0	–50.26
N_2	1027.80	3264.93	4292.73	12.85	39.18	52.03	0	–52.03
P_1	1578.50	3516.50	5095.00	19.73	42.20	61.93	67.50	+5.57
P_2	1560.15	3554.91	5115.06	19.50	42.66	62.16	135.00	+72.84
N_1P_1	4345.05	6435.26	10 780.31	54.31	77.22	131.53	67.50	–64.03
N_1P_2	4467.90	6476.54	10 944.44	55.85	77.72	133.57	135.00	+1.43
N_2P_1	4507.20	6690.18	11 197.38	56.34	80.28	136.62	67.50	–69.12
N_2P_2	5088.75	7017.05	12 105.80	63.61	84.20	147.81	135.00	–12.81

Absorbed 1.25 kg and 1.2 kg P to produce 100 kg grain in the wheat and corn, respectively. These values were the averages for wheat and corn yields from 1985 to 2007. CK – control; N_1 – 270, N_2 – 540 kg N/ha/year; P_1 – 29.5, P_2 – 59 kg P/ha/year

lizer applications. Fertilization managements have significantly influenced soil TP and RP contents (Zhan et al. 2015, Lošák et al. 2016).

Crop yield. The P balance in the soil was a result of the different fertilizer application practices and crop output (Table 4). The P balance value was negative in the CK, N_1 and N_2 treatments, where the amounts of P removed from the soil were 18.92, 21.96, 22.74 kg P/ha/year in the CK, N_1, N_2 treatments, respectively. This result was similar to the study results of Liu et al. (2003). However, the surplus P in the P_1 and P_2 treatments increased, reaching 2.43 and 31.83 kg P/ha/year, which was similar to the study results of Ma et al. (2005). The yields of wheat and corn also increased in the N_1P_1, N_2P_1 and N_2P_2 treatments, however, the P balance value was negative in these three treatments, due to the large removals of P from the soil. Soil P in the N_1P_2 treatment was in a balanced state, with 270 kg N/ha/year being applied and 59 kg P/ha/year being used for crop growth; at the same time, it did not result in large accumulations in the soil. Hence, these are the most economical rates of N and P fertilizers in this system.

Furthermore, the proportion of P taken up by the crops differed in the different treatments, in which the values changed between 1:2.58–3.36 in the no-P treatments, 1:2.14–2.19 in P-only treatments and 1:1.32–1.42 in the N and P fertilizer treatments. Therefore, corn was the crop that used the most P (Zhang and Zhang 2000), especially in the no-P and P fertilizer-only treatments.

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