The characteristics of phosphorus adsorption and desorption in gray desert soil of Xinjiang, China

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Abstract. The characteristics of phosphorus (P) adsorption and desorption in Xinjiang gray desert soil (0 - 200 mm) of China in the long-term fertilization condition is affected by the level of soil P content which studied through an isothermal adsorption and desorption experiments of P. The results stated that within the experimental concentration range, with the increase of the amount of outer-source phosphorus, P adsorption, desorption and desorption rate increased and adsorption rate decreased gradually in different Olsen-P levels of gray desert soil in Xinjiang, China. Olsen-P content is significantly correlated with the P adsorption saturation (DPS) of gray desert soil. The maximum adsorption capacity (Xm) of the treatments followed an extremely significant decreasing order of CK>NPK>NPKM>PK>NPKS. The maximum buffer capacity (MBC) and adsorption constant (K) of the NPK treatment was much higher than NPKM, NPKS, PK and CK treatments. And, MBC value of CK treatment was extremely higher than NPKS and PK, however, the differences between NPKM and CK, NPKS and PK were not significant. The comparison between NPKM, NPKS, PK and CK treatments showed no significant difference in K value, but these four showed significantly lower than NPK treatments. The value of soil easy desorption P (RDP) of NPKS and NPKM was significantly higher than NPK and PK, and the chemical fertilizer with organic fertilizer was a best way to release the phosphorus for Xinjiang agricultural production, China.

1. Introduction
Phosphorus (P) is an indispensable nutrient for plant growth and is important for agricultural production [1-4]. The content of available P is relatively low in most soils in China, so meeting the nutrient requirements of plants is difficult. The calcareous soil in northern China has strong adsorption and precipitation effects on P fertilizer; thus, many studies have focused on methods to decrease fixation and increase the effectiveness of added P in soil [5]. Since the 1950s, efforts have been made to understand the adsorption and desorption characteristics of soil P from various aspects. Boparai and Sharma [6] demonstrated that clay type and its content, and content of available P in soil (Olsen-P), played important roles in the adsorption and desorption of soil P. Chinese researchers showed that soil pH, iron and aluminum oxides, calcium, organic matter and clay content all affected the P adsorption and desorption of soil [7]. The adsorption and desorption characteristics of P in soils with diverse particle compositions [5], different clay contents [4] and various soil types [8] were significantly
different. In addition, exogenous application of humic acid [9] and polyacrylamide [10] greatly influenced the P adsorption and desorption of soil. Even using the same soil type (such as gray desert soil) under similar climate conditions, the content of Olsen-P showed significant differences of up to 30 mg·kg⁻¹ for different fertilization treatments in long-term experiments [11]. With such a great variation in the Olsen-P content of gray desert soil, what are the adsorption and desorption characteristics of soil P? What is the effect of different Olsen-P contents on the adsorption and desorption of soil P? Based on 22-year long-term fertilization experiments with gray desert soil, we studied the adsorption and desorption characteristics of soil P. This provided a basis for the appropriate utilization and management of P, as well as for optimizing fertilization in gray desert soil, Xinjiang China.

2. Materials and methods

2.1. Experimental field, climate characteristics and soil properties
Gray Desert Soil Long-term Monitoring Station in Urumqi Xinjiang is one station in the national long-term monitoring network that monitors soil fertility and fertilizer benefits. It was founded in 1989, and its primary goal is to investigate the climate characteristics, crop rotation, the effects of organic and inorganic fertilizer on crop yield, and the change in soil fertility in the northwestern agricultural region in China. The station (43°58′N, 87°25′E, with the altitude of 600 m) is located in a suburb of Urumqi, Xinjiang, in a typical continental arid climate zone. The climate characteristics of the area are as follows: annual precipitation, 242 mm; average temperature, 7.6°C; effective accumulated temperature, 1734°C; frost-free period, 156 d; and sunshine duration, 2454 h. The soil classification standard of China classes the soil in this station as typical gray desert soil; based on the standard of the United Nations Food Agriculture Organization (FAO) classification, it is a Calcaric Cambisol [12]. Before the fertilization experiments, the main soil properties in the plough layer (0-200 mm): soil pH (water: soil of 2.5:1) 8.1, organic matter 8.8 g·kg⁻¹, total nitrogen (N) 0.87 g·kg⁻¹, total P 0.67 g·kg⁻¹, total potassium (K) 23.0 g·kg⁻¹, alkaline hydrolysable N 55.2 mg·kg⁻¹, Olsen-P 3.9 mg·kg⁻¹, and NH₄OAc extractable K 288.0 mg·kg⁻¹. In 1989, prior to beginning the long-term fertilization experiments, a local cultivar of wheat was grown for 2 years (1988 and 1989) without fertilizer in order to reduce soil variation among treatments. Each following year, plants were grown for one season at the station with a rotation of wheat, maize and cotton.

In the present study, five treatments with large differences in Olsen-P were selected from the long-term fertilization experiment as shown in table 1 to study the adsorption and desorption of soil P. The five treatments were (1) control (CK), (2) P and K fertilization (PK), (3) N, P and K fertilization (NPK), (4) N, P, K and organic fertilization (NPKM) and (5) N, P and K fertilization with straw returning (NPKS). Winter wheat was planted in 2011. Fertilization in each treatment is shown in table 2.

Table 1. Soil properties (0–200 mm) of different treatments in the experiment.

| Treatments | pH | Organic matter (g·kg⁻¹) | Total N (g·kg⁻¹) | Total P (g·kg⁻¹) | Available N (mg·kg⁻¹) | Olsen-P (mg·kg⁻¹) | Available K (mg·kg⁻¹) | Bulk density (g·cm⁻³) |
|------------|----|------------------------|------------------|------------------|-----------------------|-----------------|----------------------|----------------------|
| CK         | 9.16 | 12.70 | 0.54 | 0.58 | 38.82 | 4.27C | 216.80 | 1.56 |
| PK         | 9.62 | 12.48 | 0.48 | 0.80 | 40.09 | 22.39B | 222.04 | 1.50 |
| NPK        | 9.26 | 13.30 | 0.58 | 0.92 | 70.64 | 13.61BC | 284.90 | 1.50 |
| NPKM       | 9.26 | 14.96 | 0.81 | 0.90 | 85.92 | 45.42A | 939.96 | 1.46 |
| NPKS       | 9.26 | 13.41 | 0.69 | 0.72 | 51.55 | 8.93BC | 291.97 | 1.52 |

Note: The topsoil sample collected in June 2011 was used for table 1. The indicators are the soil fertility properties determined prior to the adsorption and desorption experiments. Different capital letters following numbers represent significant differences at $P < 0.01$, the same as below.
Table 2. Average annual nutrient input from different sources during 1990–2011.

| Treatment | Chemical fertilizer | Manure | Straw |
|-----------|---------------------|--------|-------|
|           | N (kg·ha⁻¹)         | P (kg·ha⁻¹) | K (kg·ha⁻¹) | M (t·ha⁻¹) | S (t·ha⁻¹) |
| CK        | 0                   | 0      | 0     | 0          | 0          |
| PK        | 0                   | 29.2–60.2 | 18.8–50.4 | 0          | 0          |
| NPK       | 99.4–241.5          | 29.2–60.2 | 18.8–50.4 | 0          | 0          |
| NPKM      | 29.8–84.9           | 8.7–22.4 | 6.7–10.1 | 30         | 0          |
| NPKS      | 89.4–216.7          | 24.5–50.8 | 16.9–42.3 | 0          | 4.5–9      |

Note: Crops were planted without fertilizing in CK; the amount of P and K fertilizer in PK treatment was the same as that in NPK treatment; the fertilization amounts of N, P and K were 99.4, 29.2 and 18.8 kg·ha⁻¹, respectively, for 1990–1994, and were increased to 241.5, 60.2 and 50.4 kg·ha⁻¹ for 1994–2011. In Treatment NPKM, the organic manure was sheep droppings, of which the nutrient contribution was calculated on the basis of 15%, the utilization rate of organic manure in the current year and in Treatment NPKS, the nutrient contribution of the straw was calculated on the basis of 10%, the utilization rate of straw in the current year. The two treatments were designed to have the same nutrient application rates as the same as treatment NPK. Of the chemical fertilizers, all the P and K fertilizers and 60% of the N fertilizer was used as base fertilizer, and 40% of the N fertilizer as topdressing.

2.2. Evaluation items

2.2.1. Determination of soil P with isothermal adsorption. Six soil samples (2.500 g each) were placed in 100-mL centrifuge tubes, and 25 mL of 0.01 mol·L⁻¹ CaCl₂ solution with P concentrations of 0, 25, 50, 75 and 100 mg·L⁻¹ respectively added into the six tubes. In addition, three drops of chloroform were added to inhibit microbial activity. The mixture was oscillated for 1 h at 25°C and centrifuged at RCF 2770 (xg) for 8 min after incubating for 24 h and then the P concentration of the solution was determined, based on which the P adsorption in soil was calculated. The curve of isothermal adsorption was plotted using the P concentration in the solution as the X-axis and adsorptive P in soil as the Y-axis, and then fitted with an equation.

2.2.2. Determination of soil P with isothermal desorption. The supernatant of the centrifuged from the mixture was removed, and the pellet rinsed twice with 25 mL of saturated NaCl solution and centrifuged at RCF 2770 (xg) for 8 min to eliminate free P. In each tube, 25 mL of 0.01 mol·L⁻¹ CaCl₂ solution was added, with three drops of chloroform to inhibit microbial activity. The mixture was incubated for 24 h after oscillating for 1 h at 25°C, followed by centrifugation at RCF 2770 (xg) for 8 min. The resulting supernatant was used to evaluate the desorptive P, and the desorption rate was determined according to the ratio of desorptive P and total adsorptive P in the soil.

2.2.3. Determination of available P and organic matter in soil. Olsen-P in soil was determined using the 0.5 mol·L⁻¹ NaHCO₃ (pH 8.5) method. The organic matter in soil and other items were evaluated using the conventional methods of soil agrochemistry [13].

2.3. Data processing

The maximum buffering capacity of soil P (MBC, mL·g⁻¹) was calculated using constant of adsorption reaction (K) × Xₐ [14], where Xₐ is the maximum adsorption of soil P. Readily desorbable P (RDP) represented the P amount from the soil solid phase entering the liquid phase with 0 mg·L⁻¹ P addition during the adsorption and desorption process [14]. Statistical analysis was performed using SAS 9.1 and Excel 2003.

3. Results and analyses
3.1. Adsorptive characteristics of soil P

3.1.1. Isothermal adsorption curve of soil P. The adsorption curve in five treatments with various levels of soil P is shown in figures 1 and 2. With P addition in the range of 0–100 mg·L\(^{-1}\), the P adsorption was gradually elevated and the absorptive rate was reduced with increases in exogenous P. With P addition in the range 0–50 mg·L\(^{-1}\), the adsorption rapidly increased in all treatments except for PK; however, within the range 50–100 mg·L\(^{-1}\), P adsorption in soil decreased in all five treatments. In all treatments with different P levels, the adsorption rapidly increased, then slowly increased, followed by a plateau with increased exogenous application of P, but the adsorption rate showed a downward trend. To quantify the variation of P adsorption in different treatments, the isothermal adsorption equation was selected to simulate increasing exogenous P and P adsorption in soil, which facilitates study of the adsorptive characteristics of soil P under various P treatments.

![Figure 1. The P isotherm adsorption curves in different treatments.](image1)

![Figure 2. Change in P adsorption rate with extraneous P.](image2)
3.1.2. Adsorption equations of soil P. When using the equilibrium method to study P adsorption in soil systems, isothermal adsorption equations, such as Langmuir, Freundlich and Temkin [15], are commonly used to fit the relationship between the adsorption amount of the soil surface and the equilibrium concentration in solution. Then, parameters such as the adsorption amount can be calculated according to each equation. In the present study, we used the Langmuir, Freundlich and Temkin isothermal equations shown in Table 3 to simulate the isothermal adsorption process of soil P under various P levels.

The Langmuir equation is expressed as \( C/X = C/X_m + 1/(KX_m) \), where \( X \) represents the P adsorption of soil, \( C \) indicates P concentration in the equilibrium solution (The parameter of \( X \) and \( C \) are the same definition for all three equations) and \( K \) is a constant related to the energy of adsorption. The Freundlich equation is \( X = KC^b \), where \( K \) and \( b \) are two constants related to soil properties. The Temkin equation is \( X = K_1\ln C + K_2\ln K_2 \), where \( K_1 \) and \( K_2 \) are two constants related to soil properties. Simulation of soil P adsorption under the five treatments was carried out using the three isothermal adsorption equations as shown in Table 3. The significance level of Langmuir equation fitting (\( P < 0.01 \) or \( P < 0.05 \)) was higher than that of Freundlich and Temkin equations; and it showed good correlations, with all the correlation coefficients (\( r \)) > 0.95 as shown in Table 4. This suggested that the Langmuir equation was the best method to describe the adsorption characteristics of P in gray desert soil, and so we selected this equation to explore the adsorption characteristics of P in soil.

Table 3. Isothermal adsorption equations and parameters in different treatments.

| Treatment | Langmuir equation | Freundlich equation | Temkin equation |
|-----------|-------------------|---------------------|-----------------|
|           | \( C/X = C/X_m + 1/(KX_m) \) | \( X = KC^b \) | \( X = K_1\ln C + K_2\ln K_2 \) |
| CK        | 416.7 0.2131 0.99* | 0.3305 105.6 0.99 | 91.20 0.2540 1.00 |
| PK        | 244.6 0.1807 0.95* | 0.1441 119.5 0.65 | 30.72 3.0704 0.64 |
| NPK       | 333.6 0.6086 0.99* | 0.1572 177.5 0.79 | 41.24 4.0511 0.76 |
| NPKM      | 330.2 0.1969 0.99* | 0.2836 96.7 0.995 | 67.01 0.4580 0.97 |
| NPKS      | 236.1 0.2445 0.99** | 0.2834 65.4 0.99** | 48.98 0.1766 0.99** |

Note: * and ** represent statistical significance at \( P < 0.05 \) and \( P < 0.01 \), respectively. The same as below.

Table 4. Langmuir isothermal adsorption equations in different treatments.

| Treatment | Langmuir equation | \( r \) |
|-----------|-------------------|--------|
| CK        | \( C/X = 0.0024C + 0.0113 \) | 0.99* |
| PK        | \( C/X = 0.0041C + 0.0235 \) | 0.97 |
| NPK       | \( C/X = 0.003C + 0.0049 \) | 0.99** |
| NPKM      | \( C/X = 0.003C + 0.0178 \) | 0.98** |
| NPKS      | \( C/X = 0.0043C + 0.0315 \) | 0.98** |

3.1.3. Adsorption parameters of soil P. The adsorption process of P can be characterized by many parameters. The following four parameters were used in the present study:

- \( X_m \) reflects the number of adsorption sites of soil colloids [16] and indicates the P storage capacity of soil. When the soil P storage reaches a certain capacity, it is possible for the soil to provide nutrients to crops [4]. Of the five treatments, \( X_m \) was the largest for CK, 12–18 times those of other treatments, and it was significantly different (\( P < 0.01 \)) from other treatments as shown in Table 5. There was no significant difference in \( X_m \), between NPK and NPKM, and between PK and NPKS; but for NPK and NPKM, there was a much greater \( X_m \) compared with that of PK and NPKS treatments. The P input of PK and NPK treatments were the same as
shown in table 2, but the yield of PK was substantially lower than that of NPK due to the lack of N [17] – that is, the output of soil P was less than that of the NPK treatment, resulting in a relatively high P left over in soil as shown in table 1. Therefore, the soil adsorption capacity was relatively small in the PK treatment. Similarly, the output of soil P was lower in the NPKS than in the NPK treatment, and so the soil adsorption capacity was relatively small.

Table 5. The P adsorption and desorption parameters in different treatments.

| Treatment | Maximum adsorption capacity ($X_m$) (mg·kg$^{-1}$) | Adsorption constant ($K$) | Max buffer capacity of soil P ($MBC$) (mL·g$^{-1}$) | P sorption saturation ($DPS$) (%) | Readily desorbable P ($RDP$) (mg·kg$^{-1}$) |
|-----------|-----------------------------------------------|--------------------------|-----------------------------------------------|--------------------------------|----------------------------------|
| CK        | 416.7A                                        | 0.21B                    | 88.78B                                        | 1.02D                           | 0.00C                            |
| PK        | 244.6C                                        | 0.18B                    | 43.90C                                        | 8.83B                           | 0.25C                            |
| NPK       | 333.6B                                        | 0.61A                    | 202.77A                                       | 4.10C                           | 0.00C                            |
| NPKM      | 330.2B                                        | 0.20B                    | 64.37BC                                       | 14.24A                          | 3.82A                            |
| NPKS      | 236.1C                                        | 0.24B                    | 53.37C                                        | 3.87CD                          | 1.39B                            |

- The constant $K$ represents the affinity between soil colloids and phosphate ions, which is a strength factor of soil adsorption [18], reflecting the level of P adsorption of soil to a certain extent. A positive $K$-value indicates that the adsorption reaction is spontaneous at room temperature, and the magnitude of $K$ reflects the spontaneous extent of the adsorption reaction. The larger the $K$-value, the stronger the spontaneity and the more stable the products are, leading to weak P supply [4]. The $K$-values were positive in all treatments, indicating that the adsorption reactions were all spontaneous in the order of NPK > NPKS > CK > NPKM > PK. Of these, the $K$-value was significantly higher for the NPK treatment compared with the other treatments, and no substantial difference was observed among the other four treatments, suggesting that the soil P adsorption was increased after applying N, P, and K fertilizer, but the application of P and K, NPK with organic fertilizer or straw reduced the P adsorption of soil.

- $MBC$ is the product of $K$ and $X_m$ in the Langmuir equation (i.e. $MBC = KX_m$) and so is a combined parameter for the two factors of intensity of P adsorption ($K$) and capacity ($X_m$), and it is a comprehensive indicator to evaluate the soil P supplying features [16,18]. A larger $MBC$ value represents a stronger P storage capability of soil, resulting in a higher soil P supplying ability. When the intensities of P supplying ability are similar in soils, the $MBC$ value is higher and the storage of effective P is greater, so more effective P is supplied to crops by soil. When P adsorption is comparable among different soils, a larger $MBC$ value indicates a lower energy state of the adsorbed P is, and that the P can be easily used by crops, so the intensity of P supply is relatively small [19]. The $MBC$ value of the NPK treatment was much higher than for the other four treatments, and the CK treatment had substantially higher $MBC$ than the PK and NPKS treatments as shown in table 5. There was no difference among the PK, NPKM and NPKS treatments. The CK had a very large $X_m$ value, and consequently, its $MBC$ value was significantly higher than that of PK and NPKS, but less that for the NPK treatment. Due to similar values for $K$ and $X_m$ in the PK and NPKS treatments, their $MBC$ values did not significantly differ.

- The P sorption saturation ($DPS$) reflects the ratio between the content of effective P in soil and its maximum adsorption [4]: $DPS = \frac{[\text{available P in soil (Olsen-P)}/\text{maximum P adsorption}] \times 100}{\text{maximum adsorption of P calculated by the Langmuir equation}}$. The order of $DPS$ among treatments was NPKM > PK > NPK > NPKS > CK as shown in table 5. Of these, the $DPS$ of NPKS, CK and NPK did not significantly differ, but there were substantial
differences among all other treatments. The variation in \( \text{DPS} \) of all treatments was similar to the trend of Olsen-P content in soil as shown in table 1.

3.2. Desorption characteristics of soil P

3.2.1. Desorption amount and desorption rate of soil P. The desorption of P in soil is usually considered as the reverse process of adsorption, which depends on the reuse of adsorbed P. As exogenous P increased, the desorption amount of P gradually increased in soils with various P contents as shown in figures 3 and 4, indicating that the P desorption amount of soil was related to application of exogenous P. The order of the desorption amount among treatments was CK > NPKM > PK > NPKS > NPK. The desorption rate of P is represented by the ratio between the amount of desorption P and total P adsorbed before desorption, and the desorption rate had a similar pattern to that of desorption amount – it increased with increased exogenous application of P, consistent with previous results [4, 20]. The order of desorption rate among treatments was PK > NPKM > CK > NPKS > NPK, and this pattern was significantly negatively correlated with K-value as shown in table 5 – the higher the K-value, the smaller was the desorption rate in soil. The K-value of NPK was much greater than that of the other four treatments, and thus its desorption rate was relatively low as shown in figure 4.

![Figure 3](image1.png)

**Figure 3.** The P isothermal desorption curves in different treatments.

![Figure 4](image2.png)

**Figure 4.** The P isothermal desorption rates in different treatments.
3.2.2. Readily desorbable P in soil (RDP). The order of RDP among different treatments was NPKM > NPKS > PK > NPK = CK. Of these, no significant difference was observed among the RDP of the PK, NPK and CK treatments, but RDP of all other treatments varied substantially. The order of RDP values suggested that the chemical fertilizer with organic fertilizer or straw returning significantly improved the content of readily desorbable P in soil, and this effect was much greater than that of chemical fertilization alone. The RDP value of NPKM was much higher than that of the other treatments, indicating that chemical with organic fertilization greatly increased the P desorption of soil, and significantly improved the effect of available P in soil.

4. Discussion

Liu et al (2003) [11] demonstrated that the content of Olsen-P in soil significantly differed among various treatments (by almost 30 mg·kg⁻¹) after 11 years of long-term fertilization experiments in gray desert soil, Xinjiang, China. In the present study, we performed the fertilization experiments for another 11 years, and the difference in the Olsen-P content of various treatments was further magnified with a range reaching 41 mg·kg⁻¹. The long-term and different fertilization practices led to differences in the input (fertilization) and output (biomass) of P [21-23], and the adsorption and desorption of soil P changed accordingly. Here, we selected five fertilization treatments with Olsen-P content from low to high, and except for the PK treatment, they represented chronically different fertilization practices of local farmers.

The long-term biomass output without nutrient input in the CK treatment resulted in a lack of P supply in soil, leading to depletion of the soil. Therefore, CK showed a maximum Xₘ, a minimum DPS and no readily desorbable P in the isothermal adsorption experiments. The low content of effective P and high P adsorption resulted in the minimal DPS in CK (P < 0.01). The NPKM treatment exhibited a relatively large amount of readily desorbable P and a relatively low Xₘ, and thus the DPS of NPKM was much greater than that of other treatments, suggesting that the P level in soil greatly affected the amount and strength of P adsorption, consistent with previous studies [14]. Based on DPS, the P requirement for saturated adsorption at 0–200 mm depth for CK, PK, NPK, NPKM and NPKS was 1287, 670, 960, 828 and 691 kg·ha⁻¹, respectively. According to the P requirement for saturated P in gray desert soil and annual nutrient inputs, it will theoretically take about 14, 36, 44 and 26 years to saturate the P in the soil for the PK, NPK, NPKM and NPKS treatments, respectively. However, we studied the fertilized topsoil of 0–200 mm and not the whole topsoil of 0–600 mm in the present study, and the sampling time was the late growing stage of winter wheat but not post harvesting, so the actual time to reach P saturation will greatly exceed 14–44 years. This result indicates that the adsorption and desorption of P in gray desert soil is a dynamic and long-term process, and gray desert soil showed an enormous potential for P adsorption.

Compared to the two-season soil with wheat and maize rotation, the K-value of gray desert soil (0.18–0.61) was greater than that of Lou (0.07–0.12), Loessial (0.07–0.12) and Loess soils (0.06–0.10) of Shanxi Province and calcareous Chao soil of Hebei Province (0.04–0.10) [5, 24]. This was the main reason for the higher amount and stronger capability of P adsorption in the gray desert soil of Xinjiang with only one season of planting.

5. Conclusion

Within the range of 0–100 mg·L⁻¹ for exogenous P concentration, the fit for a Langmuir equation with the isothermal curve of gray desert soil reached a significant level, with r > 0.95. The P adsorption, desorption and desorption rate gradually increased with higher exogenous P application in gray desert soil for various levels of Olsen-P, but the adsorption rate was reduced. The soil content of Olsen-P in gray desert soil was significantly positively correlated with the DPS of soil—the soil Olsen-P content determined the value of DPS, indicating that Olsen-P content was a key factor affecting DPS.

The order of soil Xₘ among different treatments with various Olsen-P accumulations in gray desert soil was CK > NPK ≈ NPKM > PK ≈ NPKS, and the differences among treatments were statistically significant. No substantial difference was observed in K among the CK, PK, NPKM and NPKS...
treatments, but $K$ was significantly higher for NPK than the other four treatments. The $MBC$ of the NPK treatment was significantly higher compared with the other treatments. The $MBC$ of CK was substantially higher than for PK and NPKS, but was similar between CK and NPKM and between PK and NPKS. The $RDP$ of NPKM and NPKS treatments was much higher than for treatments with only chemical fertilization, and chemical with organic fertilization exhibited the optimal effect. Therefore, NPKM was the best fertilization practice to elevate the soil $P$ supplying capability.

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