

Agronomic threshold of soil available phosphorus in grey desert soils in Xinjiang, China

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Abstract. Based on 23 years of data, yields of maize, wheat and cotton were modelled under different fertilizer management practices and at different levels of available phosphorus (Olsen-P) in soil. Three types of threshold models were used, namely linear-linear (LL), linear-plateau (LP), and Mitscherlich type exponential (Exp). The agronomic thresholds of available phosphorus were 25.4 mg·kg⁻¹ for cotton, 14.8 mg·kg⁻¹ for wheat, 13.1 mg·kg⁻¹ for maize and 25.4 mg·kg⁻¹ for the grey desert soil regions of Xinjiang in China as a whole.

1. Introduction

Phosphorus (P) is one of the essential nutrients for plant growth as well as the key nutrient for high yield. To boost yields, farmers in China tend to apply P in excess of the recommended doses[8], which results in accumulation of P in farmland topsoil to form a huge pool of P[17]. The minimum amount of soil available P for maximum crop yield is referred to as its agronomically critical value or the threshold value of soil available phosphorus[16], which is the value used by researchers as the criterion for deciding whether to continue applying P[1,2].



Because of its unique location and climate, Xinjiang farming system is only one crop a year. Cotton, wheat, and maize are the main three produced crops in Xinjiang, accounting for 73% of the total region's cropped area (cotton, 35%; wheat, 21%; and maize, 17%)[20]. The agronomic thresholds of soil P for these three crops have not been reported for the grey desert soil region of Xinjiang for the single-crop system mentioned above—a lacuna the present study sought to fill. We used the data available from a long-term location trial to study the effect of different doses of P and soil available P on the yields of cotton, wheat, and maize and eventually determined the agronomic thresholds of soil P.

2. Materials and methods

2.1. Overview of the experimental site

The experimental site was in Xinjiang Grey Desert Soil Fertility and Fertilizer Efficiency Long-term Monitoring Station of which was one site of the National Long-term Monitoring Network of Soil Fertility and Fertilizer Effects, about 25 km north of Urumqi City, Xinjiang (43°58'23" N, 87°25'58" E) in China. The station is under the National Modern Agricultural Science and Technology Demonstration Zone of the Xinjiang Academy of Agricultural Sciences. The soil of the experimental site is the typical grey desert soil which is a major soil type in the hinterland of Eurasia, in the temperate inland region, and also in the arid desert areas of north-western China, where they are spread over 1.8×10^6 ha. About 80% of that area is in Xinjiang. The terrain of the experimental site is uneven, with higher elevations in the east and the south and lower elevations in the west and the north (the gradient is 1/100—1/70), the average being 600 m. The water table is at a depth of 30 m. The relevant weather parameters (annual averages) are as follows: precipitation, 310 mm; evaporation, 2570 mm; temperature, 7.7 °C; sunshine hours, 2594, and frost-free days, 156. The basic physical and chemical properties of topsoil (0–20 cm) were listed as Table 1.

Table 1. The basic physical and chemical properties of topsoil (0–20 cm) of Xinjiang grey desert soil.

Items	Value
Organic matter (g kg ⁻¹)	15.2
Total N (g N kg ⁻¹)	0.87
Total P(g P kg ⁻¹)	0.67
Total K (g K kg ⁻¹)	19.8
Alkali-hydrolysable N (mg N kg ⁻¹)	55.2
Available P (mg P kg ⁻¹)	3.9
Soil pH	8.1
Soil bulk density (g cm ⁻³)	1.25

Note: Table 1 is the basic physical and chemical properties of topsoil (0-20 cm) of Xinjiang grey desert soil in 1989. Uniformity trials of the grey desert soil were conducted during 1988–1989, and soil fertility and fertilizer efficiency have been monitored since 1990. Each test plot in the monitoring station is 468 m². The plots are

separated by cement boards up to a depth of 1.2 m.

2.2. Experimental design

Seven treatments from the long-term fertilizer experiments were selected for analysis: (1) CK (control; no fertilizer), (2) NK (N and K fertilizers), (3) NP (N and P fertilizers), (4) NPK (N, P, and K fertilizers), (5) NPKM2 (NPK fertilizers with a regular dose of manure), (6) NPKM1 (NPK fertilizers with overdose of manure), and (7) NPKS (NPK fertilizers with straw returned to the soil). Sheep dung was used as manure, applied once each fall at the time of ploughing, and all the straw from the current season was crushed before being ploughed back. Crop rotation and one crop a year followed the established requirements for each treatment, with maize grown in 1990, 1993, 1996, 2000, 2003, 2005, 2008 and 2010; spring wheat was in 1991, 1994, 2002 and 2006; winter wheat was in 1992, 1995, 1997, 1998, 2001, 2004, 2007 and 2011; and cotton was in 1999, 2009 and 2012. The topsoil was tested annually after harvest. The average annual nutrient inputs for each treatment are shown in Table 2.

Table 2. Average annual nutrient inputs from different sources during 1990–2015.

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
NK	99.4–241.5	0	18.8–50.4	0	0
NP	99.4–241.5	29.2–60.2	0	0	0
NPK	99.4–241.5	29.2–60.2	18.8–50.4	0	0
NPKM2	29.8–84.9	8.7–22.4	6.7–10.1	30	0
NPKM1	59.6–151.9	17.4–39.4	13.4–15.5	60	0
NPKS	89.4–216.7	24.5–50.8	16.9–42.3	0	4.5–9

Note: The application rates of N, P and K (kg ha⁻¹) for chemical fertilizer were 99.4 kg N ha⁻¹, 29.2 kg P ha⁻¹ and 18.8 kg K ha⁻¹ in 1990–1994 and 241.5 kg N ha⁻¹, 60.2 kg P ha⁻¹, and 50.4 kg K ha⁻¹ in 1995–2015 in the NPK treatment. In NPKM1 and NPKM2, the organic manure was sheep dung, which was assumed to contribute 15% of the total nutrients in the current year; the straw was assumed to contribute 10% of the total nutrients in the current year. In these treatments, the fertilizer dose was reduced proportionately, such that the total inputs of N, P, and K remained the same in all the treatments except CK. All the P and K and 60% of N were given as the basal dose, and the remaining N was given as a top dressing.

2.3. Methods of measurements

The soil available P (Olsen-P) was extracted by 0.5 mol·L⁻¹ sodium bicarbonate (NaHCO₃) at pH 8.5, and crop yields were determined from the whole plot area.

2.4. Modeling procedures

The agronomic threshold of soil Olsen-P was determined by using the functional relationship between the extent of increase in yield following long-term application of fertilizers and soil Olsen-P content. In the present study, the functional relationship between the increase in the yield of different crops (cotton, wheat, and maize) and Olsen-P content of the grey desert soil was fitted as both linear (linear-linear (LL) or linear-plateau (LP)) and nonlinear equations (Mitscherlich (Exp)). The cut-off point of the LL and LP models divided the reaction curves of the crops to soil Olsen-P content into two sections, and this cut-off point was the agronomic threshold for soil Olsen-P. In the Exp model, the point of 90% of the maximum yield on the curve served as the threshold value

The effect of externally applied P on the yield of cotton, wheat, and maize was assessed in terms of absolute yield in the present study. The absolute yield was calculated using the following equation:

$$Y_A = Y_{NPK} - Y_{CK} \quad (1)$$

where Y_A is the absolute yield, Y_{NPK} and Y_{CK} represent the yield ($\text{kg} \cdot \text{ha}^{-1}$) in the NPK and the CK treatments, respectively; thus the absolute yield is the difference in yield between the two treatments and eliminates any variations in the annual yield due to such factors as crop varieties.

The LL model can be represented as equations (2) and (3):

$$Y_1 = b_1 X + a_1 \text{ when } X < C \quad (2)$$

$$Y_2 = b_2 X + a_2 \text{ when } X \geq C \quad (3)$$

where Y_2 and Y_1 are the predicted absolute yields, a_2 and a_1 are the intercept parameters, b_2 and b_1 are the slope parameters, X is the soil available P (Olsen-P) content ($\text{mg} \cdot \text{P} \cdot \text{kg}^{-1}$), and C is the soil available P (Olsen-P) threshold ($\text{mg} \cdot \text{P} \cdot \text{kg}^{-1}$).

The LP model can be represented as equations (4) and (5):

$$Z = bX + a \text{ when } X < C \quad (4)$$

$$Z = Q \text{ when } X \geq C \quad (5)$$

where b is the slope parameter, Z is the predicted absolute yield, X is the soil available P (Olsen-P) content ($\text{mg} \cdot \text{P} \cdot \text{kg}^{-1}$), a is the intercept parameter, C is the soil available P (Olsen-P) threshold ($\text{mg} \cdot \text{P} \cdot \text{kg}^{-1}$) and Q is the predicted plateau of the increase in absolute yield.

The Exp model can be represented as equation (6):

$$W = [1 - e^{-c(X+b)}]A \quad (6)$$

where W is the predicted absolute yield, A is the maximum absolute yield, c is the effective factor, b is the soil's capacity to supply P, and X is the soil available P (Olsen-P) content ($\text{mg} \cdot \text{P} \cdot \text{kg}^{-1}$).

In fitting with either of the linear models (LL or LP), the threshold for Olsen-P is the intersection of two lines (b_1 and b_2 in equations (2) and (3) or b and Q in equations (4) and (5) in part of modeling procedures)[15,19]. Whereas, the threshold of non-linear model (Exp) is the significant response point of Olsen-P content for 90% of the total yield. Colomb et al. (2007) discuss thoroughly the simulation process and the standard deviation calculation method of the Exp model.

2.5. Data analysis

Statistical analysis was performed using the nonlinear (NLIN) procedure in SAS software[13]. Marquardt procedure was used for the LL and LP models[15]; and the Gauss–Newton procedure was used for Mitscherlich model[19].

3. Results and analyses: threshold for soil Olsen-P

The response of the yields of cotton, wheat and maize to soil Olsen-P content following long-term (23 years) application of fertilizers to the grey desert soil was fitted using three separate models (Table 3). Of the three fitted curves, the Exp model presented the highest threshold value, followed, in that order, by LP and LL (Figure 1). The soil Olsen-P threshold values for the three crops as determined by the models are given in Table 4. The soil Olsen-P threshold values of wheat were $10.3 \text{ mg} \cdot \text{kg}^{-1}$, $14.4 \text{ mg} \cdot \text{kg}^{-1}$ and $19.8 \text{ mg} \cdot \text{kg}^{-1}$ for LL, LP and Exp, respectively; maize were $9.48 \text{ mg} \cdot \text{kg}^{-1}$, $10.4 \text{ mg} \cdot \text{kg}^{-1}$ and $19.5 \text{ mg} \cdot \text{kg}^{-1}$ for LL, LP and Exp, respectively; and cotton were $18.0 \text{ mg} \cdot \text{kg}^{-1}$, $20.1 \text{ mg} \cdot \text{kg}^{-1}$ and $38.2 \text{ mg} \cdot \text{kg}^{-1}$ for LL, LP and Exp, respectively. The average threshold values of soil Olsen-P for wheat ($14.8 \text{ mg} \cdot \text{kg}^{-1}$) and maize ($13.1 \text{ mg} \cdot \text{kg}^{-1}$) were very similar (a difference of only $1.7 \text{ mg} \cdot \text{kg}^{-1}$, or less than 12%) whereas the average threshold value of soil Olsen-P for cotton ($25.4 \text{ mg} \cdot \text{kg}^{-1}$) was significantly higher than that for the other two crops (the difference was as much as $12.3 \text{ mg} \cdot \text{kg}^{-1}$, or more than 48%).

Table 3. The models about the thresholds of soil available P (Olsen-P) and yields for maize, wheat and cotton.

Crop	Model	Equation ^a	R^2 ^b	N ^c
Wheat	LL ^d	$Y_1 = -0.886 + 0.472X$ $Y_2 = 3.68 + 0.0306X$	0.763***	75
	LP ^d	$Z = -0.399 + 0.368X$ $Z = 4.91$	0.726***	
	Exp ^d	$W = 5.26(1 - e^{-0.130(X-2.10)})$	0.717***	
Maize	LL	$Y_1 = -0.204 + 0.403X$ $Y_2 = 3.278 + 0.0360X$	0.709***	46
	LP	$Z = -0.267 + 0.421X$ $Z = 4.10$	0.651***	
	Exp	$W = 4.92(1 - e^{-0.124(X-1.01)})$	0.720***	
Cotton	LL	$Y_1 = -0.214 + 0.163X$ $Y_2 = 2.61 + 0.00621X$	0.897**	12
	LP	$Z = -0.214 + 0.163X$ $Z = 3.06$	0.895***	
	Exp	$W = 3.16(1 - e^{-0.0625(X-1.34)})$	0.838***	

^a The letters “Y, Z and W” are the predicted absolute yields and X is the soil available P (Olsen-P) content (mg P kg^{-1}).

^b R^2 is determination coefficient.

^c N is the sample size.

^d LP, LL and Exp are short for linear-plateau, linear-linear and Mitscherlich models, respectively.

Table 4. Mean absolute yield and threshold of soil available P (Olsen-P) (mg P kg⁻¹).

Crop	Mean absolute yield ^a (t ha ⁻¹)	Threshold of soil Olsen-P			Mean (mg P kg ⁻¹)
		LL ^b (mg P kg ⁻¹)	LP ^b (mg P kg ⁻¹)	Exp ^b (mg P kg ⁻¹)	
Wheat	4.40 ± 0.10	10.3	14.4	19.8	14.8
Maize	3.94 ± 0.09	9.48	10.4	19.5	13.1
Cotton	2.84 ± 0.04	18.0	20.1	38.2	25.4

^a Mean ± SD.

^b LP, LL and Exp are short for linear-plateau, linear-linear and Mitscherlich models, respectively.

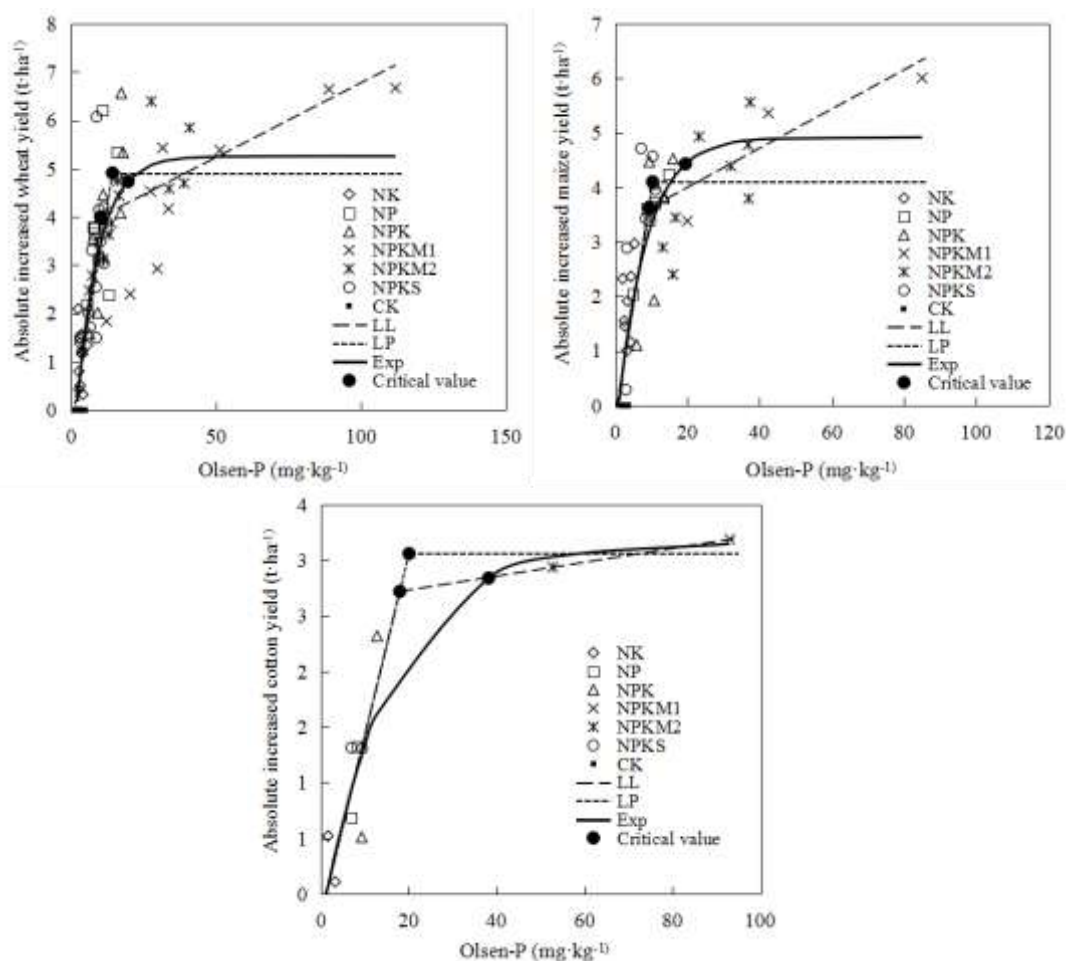


Figure 1. Response of cotton, wheat, and maize yield to soil Olsen-P fitted by LL, LP and Exp models. Note: The solid line and the dashed lines represent the curves fitted using three different models. The dots represent the agronomic threshold of Olsen-P in grey desert soil. The data for the curves are given in Table 3 and the threshold values are shown in Table 4. Abbreviations: LP, LL and Exp are Linear-Plateau, Linear-Linear and Mitscherlich model, respectively.

4. Discussion

Soil Olsen-P threshold values from the two linear models (LL and LP) were smaller than those from the non-linear model (Exp), and the average value of soil available P (Olsen-P) threshold for maize was smaller than that for wheat. All these results (the soil Olsen-P threshold values of LL and LP were smaller than Exp, and that of maize was smaller than wheat) are consistent with those of an earlier report[16]. Because the crops and the soil types in the present were different from those in the earlier report[16], the soil Olsen-P threshold value as determined from the Exp model was 1.9- to 2.1-fold of that determined by the LL model and 1.4- to 1.9-fold of that determined by the LP model. However, the soil Olsen-P threshold value was 1.4- to 2.1-fold and 1.3- to 1.9-fold for LL and LP, respectively, reported by Tang[16]. In the present study, the threshold value for wheat was 42% less than that of cotton, and the value of maize was the lowest among three crops, being 11% lower than that of wheat.

The average soil Olsen-P threshold values in the one-crop-a-year system (the crops being wheat or maize) in the grey desert soils of Xinjiang were lower those[16] proposed for the two-crops-a-year system (a rotation comprising wheat and maize) common in mainland China, indicating that the threshold values are influenced by the annual inputs of fertilizers and crop yields for different areas of crops system.

If the soil Olsen-P concentration is lower than the threshold value, yields will increase as the soil Olsen-P content increases, P being the limiting factor for high yields in this situation. Therefore, in order to increase crop yields, more P fertilizer should be applied to make the soil more fertile quickly.

If the soil Olsen-P concentration is equal to the threshold value, yields will not increase despite any increase in the soil Olsen-P content, P no longer being the limiting factor for high yields. Under these conditions, P fertilizers should be applied only to maintain the soil Olsen-P content (P input should be the same as P uptake) to ensure high yields.

Lastly, if the soil Olsen-P concentration is greater than the threshold value, yields will not respond to the addition of P, because P is not the limiting factor for high yields. Continuing application of P will result in rapid accumulation of P in soil, which will have a negative effect on production, and may even become a serious threat to groundwater and to rivers, lakes, and other freshwater bodies[5,6,9,12,14,16,17,18]. External application of P should be discontinued forthwith. The average threshold values for wheat and maize obtained in the present study fall within the ranges of 3.9–15.0 $\text{mg}\cdot\text{P}\cdot\text{kg}^{-1}$ for maize[4,10,11] and 4.9–20.0 $\text{mg}\cdot\text{P}\cdot\text{kg}^{-1}$ for wheat[3,4,7]. However, the threshold for cotton (25.4 $\text{mg}\cdot\text{kg}^{-1}$) was established in this study for the first time and has not been reported earlier.

5. Conclusion

The agronomic threshold of soil Olsen-P in the grey desert soil regions of Xinjiang was 25.4 $\text{mg}\cdot\text{kg}^{-1}$ for cotton, 14.8 $\text{mg}\cdot\text{kg}^{-1}$ for wheat, and 13.1 $\text{mg}\cdot\text{kg}^{-1}$ for maize. By relating these thresholds values to yields and measured concentrations of soil available P (Olsen-P) in Xinjiang, the agronomic threshold of soil P for the region as a whole was determined as 25.4 $\text{mg}\cdot\text{kg}^{-1}$.

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