Agronomy Research **19**(2), 423–433, 2021
https://doi.org/10.15159/AR.21.006

Soil Phosphorus management based on changes in Olsen P and P budget under Long-term fertilization experiment in fluvo-aquic soil

Kh.H.M. Ibrahim[1,2], L. Wang[1], Q. Wu[1], Y. Duan[1], Ch. Ma[3] and S. Zhang[1,*]

[1]Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences/ National Engineering Laboratory for Improving Quality of Arable Land, Beijing, 100081, P.R. China
[2]Agricultural Research Corporation (ARC), Wad Medani 126, Sudan
[3]The Center of Extending and Service of Agricultural Technique in China, 100026 Beijing, China
[*]Correspondence: zhangshuxiang@caas.cn

Received: September 3rd, 2020; Accepted: November 5th, 2020; Published: January 19th, 2021

Abstract. Excessive input of phosphorus (P) in agricultural production and its finite resources is becoming a global concern for sustainable P management. In this study, the annual P input and output were calculated in 27 Fluvo-aquic soil sites of wheat and maize agriculture cropping system in Henan province central-east of China during the period from 1998 to 2016, to quantify soil Olsen P (OP) levels and P budget at the experimental sites and calculate the optimum P fertilizer application. The maize and wheat (Triticum aestivum) recorded 14.2 and 13.6 mg kg^{-1} respectively. The change in soil OP was positively linearly correlated with the P budget ($P < 0.01$), and an increase of 2.8 mg $kg^{-}1$ in soil Olsen P for each 100 kg ha^{-1} of P budget in the 0–20 cm soil layer. Based on ACV of soil OP with P budget and the critical level of soil OP to ACV in the study area for the next five years, the recommended rate model of soil OP for maize and wheat in the study area was determined. The application amount of P fertilizer ought to be in the range of 64–85 kg P ha^{-1}. This information can help to optimize crop yield, reduce the accumulation of P in soil, and reduce the potential risk of water pollution. More research is needed about the main factors influence on P available (OP).

Key words: Olsen P, agronomic critical value, P budget, P fertilizer, maize, wheat.

INTRODUCTION

Phosphorus (P) is a very important nutrient required for optimum crop production. However, when the P fertilizer application is more than plant uptake, the residual P is accumulated in the soil (Grant et al., 2005; Rubæk et al., 2013), this may lead to environmental problems. For example, P can become soluble in water and mobile, as it enters surface water and causes algae and other unwanted plants to grow(Anju et al., 2010). Herbicides are used for weed control (Zhang, 2003). This reduces the quality of water, fish, and desirable aquatic plants (Li et al., 2010; Jarvie et al., 2013). Global P fertilizer consumption increased from approximately 4.6 to 17.5 Tg P yr^{-1} from 1961 to 2013 (Bai et al., 2013; Lu 2000). In China, P fertilizer application consumption has increased from 1.8 to 8.9 Tg P yr^{-1} from 2000 to 2013 (Yuan et al., 2017). The mean Olsen P (OP) has risen from 8–21 mg kg^{-1} during the period 1980–2011 (Wang et al., 2016). The OP ranges between 20 and 40 mg kg^{-1} in the 90% dominant Chinese arable land, whereas 9% of the agriculture soil have soil OP more than 40 mg kg^{-1}, which poses a threat to the environment (Zhong et al., 2004; Li et al., 2010).

It's useful to keep the optimal yield and properly manage the reasonable OP-value for reducing the risk of environmental pollution (Karamesouti & Gasparatos 2017). Scientists are exerting many efforts to achieve optimal OP values, thus achieving the highest productivity while maintaining the environment (Yan et al., 2013; Karamesouti & Gasparatos 2017). The definition of ACV is the level of OP after which the crop's response to P fertilization is poor or virtually nonexistent (Tang et al., 2009; Bai et al., 2013). Agronomic critical value varies with crops and sites due to the different crop P requirements and the soil properties (Colomb et al., 2007). Li et al. (2011) revealed that the critical value of soil OP extends between 4 to 15.5 mg kg^{-1} for maize and 5 to 20 mg kg^{-1} for wheat, and this coincides with the findings by (Wu et al., 2018) found that discovered the average ACV of OP for maize and wheat were 14.2 mg kg^{-1} and 14.4 mg kg^{-1}, respectively, utilizing both Mitscherlich and Linear-plateau models in Shandong province central of China. The soil OP level is generally affected by P budget; many studies found the soil OP and P budget gave significant positive linear correlation (Messiga et al., 2010; Cao et al., 2012).

Yang et al., 2015 found that in a Fluvo-aquic soil in Tianjin, China, under different treatments of P application rate, the soil OP was increased in the ranges between 1.2 and 3.6 mg kg^{-1} for every 100 kg ha^{-1} of P surplus. Also, Yang et al. (2015) found that the soil OP in the Fluvo-aquic soil at Shanxi province in China was increased by a range of 4.2–17 mg kg^{-1} for every 100 kg ha^{-1} P surplus. In Henan province, the soil OP increased by 1.2 mg kg^{-1} for every 100 kg ha^{-1} P surplus (Yuan et al., 2017). Numerous studies have shown a significant linear correlation between changes in soil OP and P budget (Cao et al., 2012; Zhan et al., 2015; Blake et al., 2000). However, they tried to determine the ideal P application rate depending on the reaction of OP in Fluvo-aquic soil to changes in P budget, considering both the ACV and environmental risks (Cao et al., 2012; Zhang et al., 2019). The aims of this research were (i) to estimate the annually P input-output during the period of the experiment (1998–2016), (ii) to calculate the optimum P fertilizer rate through the correlation between soil OP and P budget and (iii) the wheat and maize response to P fertilizer application, which will be helpful for the sustainable management of P fertilizer application in the research area.

MATERIALS AND METHODS

Experimental location and soil properties

A long-term experiment was conducted in Henan Province, Central-east of China to study the yield response of the wheat and maize system to P fertilizer application. The experiments were established in 1998 on Fluvo-aquic soil, located at Luoyang, Sanmenxia, Anyang, Nanyang, Zhoukou, Xinxiang, Kaifeng, Shangqiu and Puyang, with latitude (N) and longitude (E) range of 33°48'–34°40' N and 111°20–112°44′ E, respectively (Fig. 1). The climatic condition is classed as semi-tropical with the mean annual temperature 14 °C, and the annual precipitation ranges from 600–1,200 mm during the experimental period 1998–2016 (Table 1).

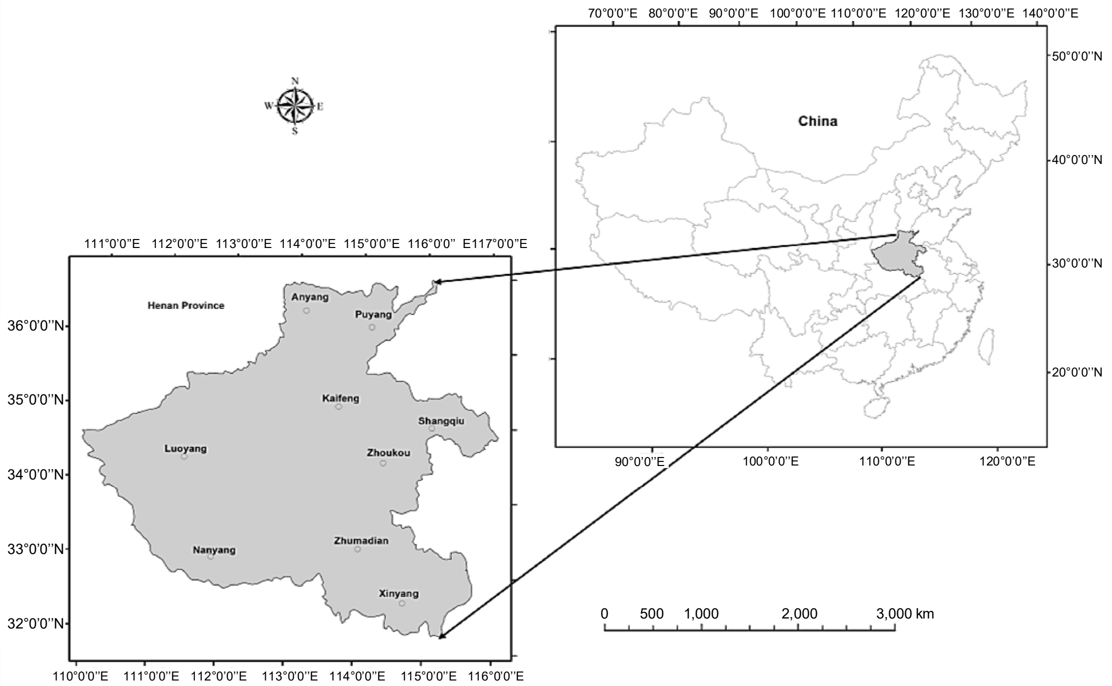

Figure 1. Sampling locations in nine cities in Henan province, central east China in the period between 1998–2016.

Soil and Plant analysis

Soil samples were gathered from depth 0 to 20 cm in the observing seasons after wheat harvest in autumn. Five soil samples were collected from each plot and thoroughly mixed to form a composite sample, air-dried at room temperature (20–25 °C) and sieved through a 2.0 mm sieve. Shake a 2.5 g soil sample with 50 ml 0.5 mol L^{-1} $NaHCO_3$ at 25 °C for 30 minutes, filter the suspension, and use the molybdate ascorbic acid method to determine the P concentration in the filtrate (Murphy & Riley 1962). Soil samples were analyzed for soil organic C (Walkley & Black, 1934), available P (Olsen, 1954), total P (Lu, 2000) and pH in water (1:2.5 soil to water ratio (Thomas, 1996). Total nitrogen was determined using micro-Kjeldahl digestion. Crop samples (grains and straw) were taken at harvest (maturity stage) plants were collected from the center strip of every plot. After drying, the crop samples were ground to pass 0.15 mm sieve to use for chemical analyses. To determine the total P content, plant powder samples were digested with H_2SO_4 H_2O_2, and the concentration in the digestion solution was determined by molybdenum blue colorimetric method (Scudder et al., 1996).

Table 1. The initial soil properties (average value) in the study area in Henan province, central east China

Item	Unit	The average value
Organic C	g kg^{-1}	14.8
Total N	g kg^{-1}	0.96
Available N	mg kg^{-1}	79.0
Olsen P	mg kg^{-1}	11.6
Available K	mg kg^{-1}	118.0
Soil pH	-	7.8

Data processing and calculation

P budget and Olsen P levels

The P budget in this research is related to the direct input and output of P. The processes for estimating P budget and OP level changes were similar at all locations. At the location level, the P budget was calculated by subtracting P output from P input (Messiga et al., 2010). The P uptake is determined according to P concentration in aboveground biomass (straw and grain). The seasonally P budget for every study area was calculated. The P loss caused by runoff and erosion is negligible. The change of OP was obtained by linear regression with the times. A long-term experiment was conducted to establish a prediction model of soil OP accumulation in wheat and maize cropping system, by using the amount of phosphate fertilizer, crop yield and cultivation time. The change of OP in the soil can be described by the following equation:

$$OP_f = OP_i + D \cdot (P_m - C_m Y_m) \cdot t \quad (1)$$

where OP_f – the final OP level; OP_i – the initial OP level; t – the time of cultivation; P – the P fertilizer addition rate; C – the concentration of P in crop grain. Y – the total crop yield per year. The $_m$ – indicates the mean of P, C, and Y during the agriculture period. D – the change in OP (C_{OP}) resulting from a one-unit change in the soil P budget (PB), which is estimated as follows:

$$C_{OP} = f + D \cdot P_B \quad (2)$$

where C_{OP} – the change in OP (mg kg^{-1}); P_B – P budget (P input – P output) kg ha^{-1} and f – the intercept parameter. The mean P fertilizer requirement was calculated by the following equation:

$$P_r = \frac{OP_f - OP_i}{D_t + P_h} \quad (3)$$

where Pr – the mean P fertilizer requirements; D is the slope of the line from the correlation between change in OP and P budget. The (Table 2) below shows the application rate of NPK in all experimental sites during the period of study.

Table 2. The application rate of the annual average Nitrogen (N), Phosphorus (P) and Potassium (K) NPK fertilizers (kg ha^{-1}) in the study area from 1998 to 2016 in Henan province, central east China

Site	Year	N	P	K
	(kg ha^{-1} yr^{-1})			
Luoyang (n = 3)	2004–2016	355 ± 23	83 ± 9	116 ± 16
Zhumadian(n = 3)	2003–2016	408 ± 30	78 ± 9	133 ± 24
Anyang (n = 2)	2000–2016	405 ± 22	81 ± 6	137 ± 9
Nanyang (n = 3)	1998–2016	335 ± 17	88 ± 13	120 ± 17
Zhoukou (n = 2)	2005–2016	418 ± 20	77 ± 9	121± 20
Xinxiang (n = 1)	1998–2016	458 ± 23	74 ± 2	126 ± 4
Kaifeng (n = 5)	1999–2016	273 ± 23	61 ± 7	86 ± 7
Shangqiu (n = 6)	1988–2016	386 ± 18	96 ± 8	144 ± 13
Puyang (n = 2)	1998–2016	414 ± 19	84 ± 9	101 ± 10

n is the number of sites observation.

Model description

To eliminate differences between years and locations, the relative yield is calculated as follows:

$$Y_r = Y_i \div Y_m \cdot 100 \quad (4)$$

where Y – the relative yield; Y_i – the annual crop yield of every treatment (kg ha^{-1}) and Y_m – the high annual crop yield (kg ha^{-1}).

Crop Agronomic critical value (ACV) can be simulated by Mitscherlich and linear-linear fitting.

The ACV of crops can be simulated by the Mitscherlich model (Johnston et al., 2013) as follows:

$$Y = \alpha \cdot [1 - exp(-bx)] \quad (5)$$

where Y – foreseen relative yield; a – high achievable yield; when x – unrestricted; b – the response factor and x is the OP concentration in soil (mg kg^{-1}).

The linear-linear model is defined by Eqs (6) and (7)

$$Y = A_1 + B_{1x}, \quad if\ x < C \quad (6)$$

$$Y = A_2 + B_{2x}, \quad if\ x \geq C \quad (7)$$

where A_1 (or A_2) – the intercept parameter; B_1 (or B_2) is the slope parameter; x – the soil OP concentration (mg kg^{-1}) and C – the critical value of soil OP.

Statistical analysis

Data processing

Mitscherlich and Linear- linear models for calculating crop ACV were simulated with sigma plot 12.5 (SYSTAT Software, San Jose, California, USA). Data were analyzed using one-way ANOVA to check its significance and averages were separated according to Duncan test at $P \leq 0.05$. SPSS 20.0 was used to normalize the experimental data to ensure the reasonable distribution of data.

RESULTS

The grain yield and experimental year

Fig. 2 shows a grain yield of maize and wheat for 19 years under long-term fertilization experiment in the study area. Only the significant differences in the grain yield of maize and wheat during 2014–2016 were observed compared with other periods.

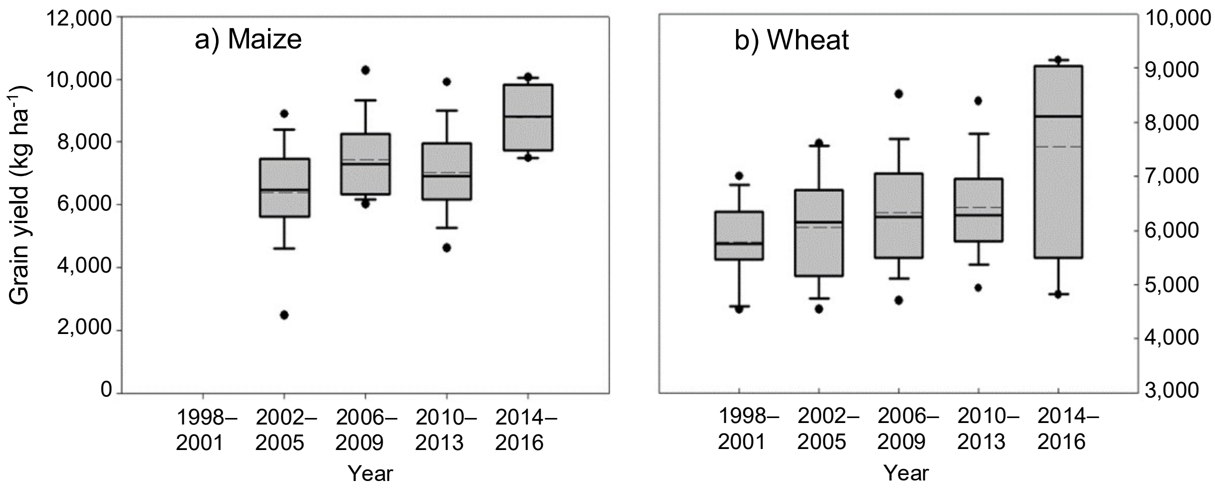

Figure 2. Simulated mean and median grain yield of maize (a) and wheat (b) over 19 years of observation in the study area under long-term fertilization experiment. black solid and The gray dash lines, lower and upper edges, and bars in or outside the boxes represent median and mean values, 25th and 75th, 5th and 95th, and, < 10th and > 90th percentiles of all data, respectively.
Different lower-case letters denote significant differences in the grain yield (Duncan's multiple range tests; $p < 0.05$).

The maximum and minimum grain yield of maize was 11,550 and 2,122.5 kg ha^{-1} in 2014–2016 and 2010–2013 respectively, meanwhile the maximum and minimum grain yield of wheat were 9,150 and 4,125 kg ha^{-1} in 2014–2016 and 2006–2009 respectively. The variation in the yield due to the change in the ACV from low to optimum by applied fertilizer. The mean grain yield for wheat and maize significantly increased with time and more NPK fertilizer application as shown in (Tables 3 and 4).

Table 3. The grain yield of wheat during the study period 1998–2016 with NPK fertilizer application

Period	Means grain yield (kg ha^{-1})
1998–2001	5,736
2002–2005	5,944
2006–2009	6,166
2010–2013	6,360
2014–2016	7,060

Table 4. The grain yield of maize during the study period 1998–2016 with NPK fertilizer application

Period	Means grain yield (kg ha^{-1})
1998–2001	6,440
2002–2005	6,570
2006–2009	7,310
2010–2013	7,005
2014–2016	8,894

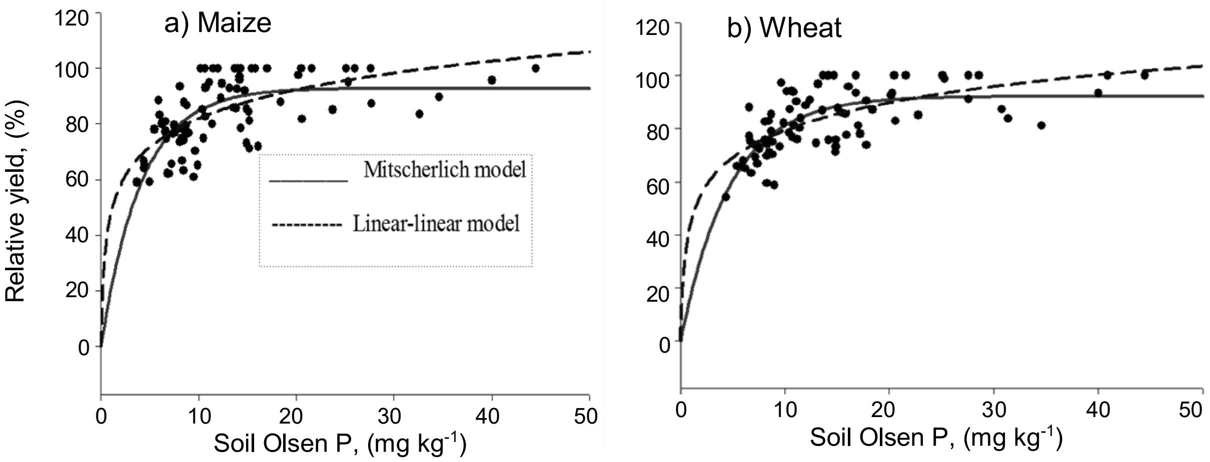

Figure 3. The grain yield of maize (a) and wheat (b) response to soil Olsen P content based on the Mitscherlich and Linear-linear model for all of the experimental sites.

To Determination ACV of OP, the crop yield was affected to soil OP level as appeared in Fig. 3, and the data of all test locations (27 locations) are consistent with Mitscherlich and linear-linear models as shown in (Table 5). The ACV value of OP for wheat and maize was 15.2 and 14.7 mg kg^{-1}, respectively, for the Mitscherlich model. The ACV amounts of OP for maize and wheat were 13.6 and 11.9 mg kg^{-1} respectively, for Linear-linear model. We observed the ACV of OP by the Mitscherlich model was higher than that value by Linear- Linear model. The average ACV of OP for maize and wheat were 14.2 and 13.6 mg kg^{-1} respectively, for both models.

Table 5. The agronomic critical value of Olsen P (mg P kg^{-1}) for all experimental sites during the period (1998–2016) in Henan province, central east China

	Mitscherlich		Linear-Linear			
Crop	Value	R^2	Value	R^2	Mean value	n
Maize	14.7	0.43**	13.6	0.39**	14.2	84
Wheat	15.2	0.47**	11.9	0.42**	13.6	84

R^2 is the coefficient of determination for Mitscherlich and Linear- Linear models (** represents $P < 0.01$); n is the number of observations used to fit the equation.

The Olsen P level and P budget

Changes in OP level and P budget in 27 experimental locations appeared in (Table 6). The mean annual P input of 101.2 kg P ha^{-1} was recorded as highest in Luoyang site, whereas the lowest average annual P input of 60.8 kg P $ha^{-1}$was recorded on Kaifeng. It was observed that Zhumadian recorded the highest average annual P output (76.3 kg P ha^{-1}), while the least mean annual P output (46.2 kg P ha^{-1}) was on Kaifeng. The average annual P budget ranged between 3.8 and 38 kg P ha^{-1} in Xinxiang and Shangqiu respectively. The initial OP level ranged between 10.4 and 20.4 mg kg^{-1}, and the final OP level ranged between 14.6 and 28.8 mg kg^{-1} as shown in (Table 6).

Table 6. Annual average P input-output, P budget and change in Olsen P in wheat-maize systems different sites in Henan province during (1998 to 2016)

Site	P input	P output	P budget	Initial OP	Final OP	Change OP
	(kg P $ha^{-1}yr^{-1}$)[a]			mg kg^{-1}	mg kg^{-1}	(mg $kg^{-1}yr^{-1}$)[b]
Luoyang (*n* = 3)	101.2	64	37.2	10.4	17.6	0.28
Zhumadian (*n* = 3)	88.7	76.3	12.4	12.8	15.5	0.21
Anyang (*n* = 2)	84.6	74.7	9.9	12.2	28.8	0.14
Nanyang (*n* = 3)	92.1	65.4	26.7	10.7	24.9	0.46
Zhoukou (*n* = 2)	61.9	47.8	14.1	12.5	20.4	0.18
Xinxiang (*n* = 1)	74.5	70.7	3.8	20.4	27.3	0.19
Kaifeng (*n* = 5)	60.8	46.2	14.6	18.7	27	0.31
Shangqiu (*n* = 6)	95.9	57.9	38	19.2	20	0.34
Puyang (*n* = 2)	84	72.8	11.2	10.4	14.6	0.1

n is the number of sites observation; [a] The annual average P input, P output and P budget (kg P ha^{-1} $year^{-1}$); [b] Change in Olsen P(OP) was the slope values getting from the linear regressing of dynamic of Olsen P with years (mg $kg^{-1}year^{-1}$).

Fertilizer P Recommended based on Olsen P and P budget

Table 7. Annual average P fertilizer application rate Recommended for wheat and maize cropping systems at different sites in the study area during (1998 to 2016)

Site	Duration years	P input	P output	OP_m	OP_p	Range in OP	Recommended P in next 5 years
		(kg P $ha^{-1}Yr^{-1}$)[a]		mg kg^{-1}			(kg P $ha^{-1}Yr^{-1}$)[a]
Luoyang (*n* = 3)	12	101.2	64	17.6	27.7	15.240	64.0
Zhumadian (*n* = 3)	13	88.7	76.3	15.7	22.9	15.240	76.3
Anyang (*n* = 2)	14	84.6	74.7	28.8	32.1	15.2 40	74.7
Nanyang (*n* = 3)	12	92.1	65.4	24.9	25.7	15.2 40	65.4
Zhoukou (*n* = 2)	12	61.9	47.8	20.4	15.8	15.2 40	47.8
Xinxiang (*n* = 1)	17	74.5	70.7	27.3	23.2	15.2 40	70.7
Kaifeng (*n* = 5)	13	60.8	46.2	27	19.7	15.2 40	46.2
Shangqiu (*n* = 6)	15	95.9	57.9	20	15.6	15.2 40	57.9
Puyang (*n* = 2)	14	84	72.8	14.6	8.6	< 15.2	85.5

[a] The annual average P input, P output budget and Recommended Fertilizer P rate in next 5 years (kg P ha^{-1} $year^{-1}$) Olsen P_p was the predicted Olsen P and Olsen P_m was the measured Olsen P in 2016 (mg kg^{-1}).

The model was tested using existing data sets collected from 27 locations. Until 2016, only one location in Puyang City had current OP levels below than the ACV 15.2 mg kg^{-1} as shown in (Table 7). To raise the low OP level to the ACV in the next five years from 2016, the P fertilizer addition amount was estimated based on Eq. (3). For other locations, the OP level was more than 15.2 mg kg^{-1} (ACV) but less than the environmental critical level of 40 mg kg^{-1} (Li et al., 2011). The level of soil OP should be maintained by calculating the annual P addition rate. Basing on the absorption of P by crops, the utilization efficiency of P should be improved to obtain the best crop production.

A model of P fertilizer recommendation rate that integrated values of the change in soil OP in response to P budget and the ACV of OP was used, to adjust current levels of soil OP to the ACV at the experimental sites over the next five years, P fertilizer application rate should be in the range of 64–85 kg P ha^{-1}.

DISCUSSION

Determination agronomic critical value of Olsen P

The critical level of OP can be definited as ‘soil P status, beyond which crop yield is not affected by P fertilizer application’ (Tang et al., 2009; Bai et al., 2013; Sucunza et al., 2018). In our study, the mean ACV of OP for maize crop was 14.2 mg kg^{-1}, inside the range from 7–18 mg kg^{-1} as defined by others (Bollons & Barraclough 1999; Colomb et al., 2007; Bai et al., 2013; Johnston et al., 2013; Poulton et al., 2013). The average of ACV of OP for wheat was13.6 mg kg^{-1} as shown in (Table 5) is similar to the higher limit of 7–11 mg kg^{-1} as reported in the previous studies, by Mitscherlich and Liner-Liner models for both crops (Colomb et al., 2007; Bai et al., 2013). The change of the critical value of the same crop in different studies was caused by the difference of test type (data type), soil properties (pH value, clay content, soil structure, organic carbon, etc.) and climatic factors (Tang et al., 2009; Johnston et al., 2013). These factors will eventually affect P recommended to farmers. In this study, the ACV of OP from the Linear-linear model is lower than that of the Mitscherlich model, which is consistent with former researches. (Mallarino & Schepers 2005; Tang et al., 2009). The ACV of soil OP obtained by using the Mitscherlich model for maize 14.7 mg kg^{-1} and wheat 15.2 mg kg^{-1} were closer to the average critical levels determined by the three models noted by (Tang et al., 2009), with an average OP level for maize and wheat was 15.2 and 16.2 mg kg^{-1}, indicating that the Mitscherlich model can be used to estimate ACV of Fluvo-aquic soil.

The Olsen P level influencing by P budget

Many researchers have determined the correlation between change in soil OP and P budget for different soil types and climate. Cao and others (2012) reported that the OP level increased from 1.5 to 5.8 mg kg^{-1} per 100 ha^{-1} P surplus at different locations. The change of soil OP in different locations was varied according to the P budget. This difference is caused by different planting systems and environmental factors (Cao et al., 2012), and soil properties (soil pH, temperature, clay content and organic matter) all affect the adsorption and desorption of P (Zhang et al., 2009). Also, the soil P adsorption capacity in warm regions is stronger than that in temperate zones (Malhi et al., 2009). For example, in warm climate regions, OP increased by 2 mg kg^{-1} for each 100 kg ha^{-1} P surplus in the soil (Aulakh et al., 2007), In temperate soils, OP increased by 6 mg kg^{-1} for every 100 kg ha^{-1}. the experimental location had a warm temperate soil and it’s affected by the air temperature in the study area (mean annual temperature 14 °C), in our experiment, the soil OP increased by 2.8 mg kg^{-1} for every 100 kg ha^{-1} P surplus, as mentioned above, it is in the range of 2 to 6 mg kg^{-1}. Yang et al. (2015) noted in a long-term experiment, the soil OP increased by 2.4 mg kg^{-1} for each 100 kg ha^{-1} P surplus for Fluvo-aquic soil in Shaanxi Province in China (geographically close to our study area), which agree with our results.

Fertilizer Phosphorus Recommended based on Olsen P critical value

The best management of P fertilizers is very important for high crop yield and environmental protection. Many studies focused on estimating rational P fertilizer application rates in China: appropriate application rate of phosphorus fertilizer was calculated based on high yield and high P use efficiency of soybean in Heilongjiang province (Li et al., 2010). Ma et al. (2011) determined the appropriate amount of P depended on the effect of P fertilizer on rice yield increasing. There were also studies estimating P fertilizer application rates based on changes in soil Olsen P. Li et al. (2012) utilized a model to calculate P fertilizer required improving the OP level to 40 mg kg^{-1}, but the ACV of OP was not considered. In this study, according to ACV and environmental critical value of soil OP, and using the calculated values of soil P budget, we put forward suggestions on the addition of P fertilizer in Fluvo-aquic soil.

Li et al. (2011) adopted the cumulative maintenance method for P controlling and delivered an experimental method, because when the OP level is less than 20, 20–40 or more than 40 mg kg^{-1}, the addition P amount should be 1.7 to 2 times of the amount of P absorbed by plants, the same to the amount of P absorbed by plants, or no addition, respectively. When the level of OP was more than 20 mg kg^{-1}, the amount of P applied by using our method and Li's method was equal to the absorption value of P by crops. When the OP level was 15.2–20 mg kg^{-1}, the amount of P applied was 1.7 times that of P uptake, in our study, and also the same in Li’s method. When the OP level was less than 15.2 mg kg^{-1}, the P addition amount estimated by Li's method was 123.8 kg P ha^{-1}, which was also more than that value in our method as shown in (Table 7). From saving limited P resources, the application amount of P can be estimated by using our method, because this method is more accurate in determining the amount of P fertilizer application to obtain optimum productivity.

CONCLUSIONS

The mean agronomic critical value of OP for maize was 14.2 mg kg^{-1}and for wheat was 13.6 mg kg^{-1} when using the Linear- Linear and Mitscherlich model. The increase in soil OP in the 0–20 cm topsoil layer was 2.8 mg kg^{-1} for each 100 kg ha^{-1} P budget. P fertilizer application rate in the following five years was calculated based on the ACV of OP and the increase in soil OP due to P surplus. This information is useful for optimizing crop production, diminishing P accumulation in soil, and reducing the potential risks of water body contamination.

ACKNOWLEDGEMENTS. This work is supported by the National Key Research and Development Program of China (2016YFD0200301) and by the Special Fund for Agro-scientific Research in the Public Interest of China (201503120). We thank all staff for their valuable work associated with these long-term Monitoring Networks of Soil Fertility and Fertilizer Effects in China.

REFERENCES

Anju, A., Pandey, R.S. & Sharma, B. 2010. Water pollution with special reference to pesticide contamination in India. *Journal of Water Resource and Protection* **2010**. doi 10.4236/jwarp

Aulakh, M.S., Garg, A.K. & Kabba, B.S. 2007. Phosphorus accumulation, leaching and residual effects on crop yields from long-term applications in the subtropics. *Soil Use and Management* **23**(4), 417–427.

Bai, Z., Haigang, L., Xueyun, Y., Baoku, Z., Xiaojun, S., Boren, W., Dongchu, L., Jianbo, S., Qing, C. & Wei, Q. 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. *Plant and Soil* **372**(1–2), 27–37.

Blake, L.S., Mercik, S., Koerschens, M., Moskal, S., Poulton, P.R., Goulding, K.W.T., Weigel, A. & Powlson, D.S. 2000. Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments. *Nutrient Cycling in Agroecosystems* **56**(3), 263–275.

Bollons, H.M. & Barraclough, P.B. 1999. Assessing the phosphorus status of winter wheat crops: inorganic orthophosphate in whole shoots. *The Journal of Agricultural Science* **133**(3), 285–295.

Cao, N., Xinping, Ch., Zhenling, C. & Fusuo, Zh. 2012. Change in soil available phosphorus in relation to the phosphorus budget in China. *Nutrient Cycling in Agroecosystems* **94**(2–3), 161–170.

Colomb, B., Debaeke, P., Jouany, C. & Nolot, J.M. 2007. Phosphorus management in low input stockless cropping systems: Crop and soil responses to contrasting P regimes in a 36-year experiment in southern France. *European journal of agronomy* **26**(2), 154–165.

Grant, C., Shabtai, B., Marcia, M., Christian, P. & Christian, M. 2005. Soil and fertilizer phosphorus: Effects on plant P supply and mycorrhizal development. *Canadian Journal of Plant Science* **85**(1), 3–14.

Jarvie, H.P., Andrew, N., Sharpley, P.J.A.W., Thad, S.J., Brian, E.H. & Colin, N. 2013. Phosphorus mitigation to control river eutrophication: Murky waters, inconvenient truths, and postnormal science. *Journal of Environmental Quality* **42**(2), 295–304.

Johnston, A.E., Poulton, P.R. & Robin, P. W. 2013. Plant-available soil phosphorus. Part II: the response of arable crops to Olsen P on a sandy clay loam and a silty clay loam. *Soil Use and Management* **29**(1), 12–21.

Karamesouti, M. & Dionisios, G. 2017. Sustainable management of soil phosphorus in a changing world. In *Adaptive Soil Management: From Theory to Practices*, pp. 189–214. Springer.

Li, H., Huang, G., Meng, Q., Ma, L., Yuan, L., Wang, F., Zhang, W., Cui, Z., Shen, J. & Chen, X. 2011. Integrated soil and plant phosphorus management for crop and environment in China. A review. *Plant and Soil* **349**(1–2), 157–167.

Li, J.M., Gao, J.S., Liu, J., Xu, M.G. & Ma, Y.B. 2012. Predictive model for phosphorus accumulation in paddy soils with long-term inorganic fertilization. *Communications in soil science and plant analysis* **43**(13), 1823–1832.

Li, Y.Y., Liu, S.Q., Ji, J.H., Ying, L., Zhang, M.Y., Guang, H., Tong, Y.X., Wei, W. & Dong, S. C. 2010. Study on the optimum rate of phosphoric fertilizer in Soybean in Heilongjiang Province. *Heilongjiang Agricultural Sciences* **6**, 48–52.

Lu, R.K. 2000. Analysis methods of soil agricultural chemistry. *China Agricultural Science and Technology Press.* Beijing **107**, pp. 147–150.

Ma., Wenqi., Lin, M., Jianhui, L., Fanghao, W., István, S. & Fusuo, Z. 2011. Phosphorus flows and use efficiencies in production and consumption of wheat, rice, and maize in China. *Chemosphere* **84**(6), 814–821.

Malhi, S.S., Brandt, S.A., Lemke, R., Moulin, A.P. & Zentner, R.P. 2009. Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and nutrient balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems* **84**(1), 1–22.

Mallarino, A.P. & Schepers, J.S. 2005. Role of precision agriculture in phosphorus management practices. *Phosphorus: Agriculture and the Environment* **46**, 881–908.

Messiga, A.J., Ziadi, N., Daniel, P., Parent, L.E. & Christian, M. 2010. Long-term changes in soil phosphorus status related to P budgets under maize monoculture and mineral P fertilization. *Soil use and Management* **26**(3), 354–364.

Murphy, J. & John, P.R. 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica chimica acta* **27**, 31–36.

Olsen, S.R. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate:US Department of Agriculture. doi.org/10.1080/00103624.2014.91130

Poulton, P.R., Johnston, A.E. & Robin, P.W. 2013. Plant-available soil phosphorus. Part I: the response of winter wheat and spring barley to Olsen P on a silty clay loam. *Soil Use and Management* **29**(1), 4–11.

Rubæk, G.H., Kristian, K., Svend, E.O., Hans, S.Ø. & Goswin, H. 2013. Phosphorus accumulation and spatial distribution in agricultural soils in Denmark. *Geoderma* **209**, 241–250.

Scudder, S.J., John, E.F. & Mary, E.C. 1996. Soil science and archaeology. In *Advances in agronomy*, Elsevier, pp. 1–76.

Sucunza, F.A., Flavio, H.G.B., Fernando, O.G., Miguel, B. & Gerardo, R. 2018. Long-term phosphorus fertilization of wheat, soybean and maize on Mollisols: Soil test trends, critical levels and balances. *European journal of agronomy* **96**, 87–95.

Tang., Xu., Yibing, M., Xiying, H., Xiuying, L., Jumei, L., Shaomin, H. & Xueyun, Y. 2009. Determining critical values of soil Olsen-P for maize and winter wheat from long-term experiments in China. *Plant and Soil* **323**(1–2), 143–151.

Thomas, G.W. 1996. Soil pH and soil acidity. In Methods of soil analysis. Part 3. Chemical methods.(Ed. DL Sparks). *Soil Science Society of America: Madison, WI*, pp. 475–490.

Walkley, A. & Armstrong, I.B. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science* **37**(1), 29–38.

Wang, B., Liu, H., Hao, X.Y., Wang, X.H., Sun, J.S., Li, J.M. & Ma, Y.B. 2016. Agronomic threshold of soil available phosphorus in grey desert soils in Xinjiang, China. *Earth Environ. Sci.* **41**, 012010.

Wu, Q., Shuxiang, Z., Yi, R., Xiaoying, Z., Minggang, X. & Gu, F. 2018. Soil phosphorus management based on the agronomic critical value of Olsen P. *Communications in Soil Science and Plant Analysis* **49**(8), 934–944.

Yan, Z., Pengpeng, L., Yuhong, L., Lin, M., Ashok, A., Zhengxia, D., Qing, C. & Fusuo, Z. 2013. Phosphorus in Chinas intensive vegetable production systems: overfertilization, soil enrichment, and environmental implications. *Journal of Environmental Quality* **42**(4), 982–989.

Yang, J., Gao, W. & Ren, S.R. 2015. Response of soil phosphorus to P balance under long-term fertilization in fluvo-aquic soil. *Scientia Agricultura Sinica* **48**(23), 4738–4747.

Yuan, T.Y., Wang, J.Z., Ji, J.H., Niu, J.Y. & Lan, M. 2017. Changes in soil available phosphorus and its response to phosphorus balance under long-term fertilization in Fluvo-aquic soil. *Journal of Nuclear Agricultural Sciences* **31**(1), 125–134.

Zhan, X., Li, Z., Baoku, Z., Ping, Z., Shuxiang, Z. & Minggang, X. 2015. Changes in Olsen phosphorus concentration and its response to phosphorus balance in black soils under different long-term fertilization patterns. *PLoS One* **10**(7), e0131713.

Zhang, H.M., Wang, B.R., Ming, G.X.U. & Ting-Lu, F.A.N. 2009. Crop yield and soil responses to long-term fertilization on a red soil in southern China. *Pedosphere* **19**(2), 199–207.

Zhang, W.W., Xiao, Y.Z., Shuxiang, Z., Khalid, H.M.I. & Ming, X. 2019. Response of soil Olsen-P to P budget under different long-term fertilization treatments in a fluvo-aquic soil. *Journal of integrative agriculture* **18**(3), 667–676.

Zhang, Z.P. 2003. Development of chemical weed control and integrated weed management in China. *Weed Biology and Management* **3**(4), 197–203.

Zhong, X., Xiaorong, Z., Huajun, B., Haohao, L., Guitong, L. & Qimei, L. 2004. The evaluation of phosphorus leaching risk of 23 Chinese soils I. Leaching criterion. *Acta Ecologica Sinica* **24**(10), 2275–2280.