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Development of a Novel Model of Soil Legacy P Assessment for Calcareous and Acidic Soils

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Phosphate (P) rock is a finite natural resource, and its use for P fertilizer production has resulted in its rapid depletion worldwide. In order to reduce the use of natural P resources, reducing the input of P into agricultural systems is necessary. The assessment of legacy P in soil is an option to maintain crop yield with low P fertilizer input. Many models have been tested to assess the contribution of legacy soil P to crop uptake. However, these models face a common challenge as conceptual soil P pools in models cannot be accurately initiated and evaluated using measured soil P indexes. In this study, a novel legacy P assessment (LePA) model was developed according to empirical equations about crop P uptake, soil Olsen-P, and total P from two long-term fertilizer experiments in typical calcareous and acidic soils in China. We used the DPPS (dynamic phosphorus pool simulator) model as a contrast model to estimate the simulation accuracy of the new LePA model. The calibration and validation datasets for both models were set-up by collecting data from two long-term fertilizer experiments in typical calcareous and acidic soils in China. The results showed that the LePA model simulated crop P uptake similar to the DPPS model in calcareous soil. While the DPPS model failed to depict crop P uptake under low pH conditions, the LePA model worked well after modification when limited crop growth caused by acidic conditions was considered. Moreover, the LePA model can also predict changes in soil TP and Olsen-P with P fertilizer application, which are new functions compared with the DPPS model. Based on a scenario analysis generated by the LePA model, P fertilizer application could be reduced by 52% in Yangling and 46% in Qiyang compared with the conventional application rate during this period to maintain the current yields if soil legacy P can be utilized efficiently. The LePA model is a useful tool for guiding soil P management from the field to country scales.

Keywords: legacy soil P, crop P uptake, soil Olsen-P, soil TP, LEPA, DPPS

INTRODUCTION

Phosphorus (P) is an essential element for plant growth (Smil, 2000; Koning et al., 2008). All modern synthetic P fertilizers are sourced from finite phosphate rock reserves (Syers et al., 2008; Cordell and White, 2011). To ensure food demand for an increasing global population in recent decades, world phosphate rock production is continuously increasing (Tilman et al., 2002; Lott et al., 2011). The economically exploitable reserves of phosphate rocks could be depleted within the next century at the present pace of 170 million tons year^{-1} (Cordell et al., 2009; Gilbert, 2009). Currently, China is the largest global producer of phosphate rock (43 Mt P_2O_5 and 53% of world total in 2017) (USGS., 2017), with the production and consumption of P fertilizer being 34 and 18 Mt P_2O_5 in 2017, respectively (NBS., 2017). In China, as in other countries of the world, only 20% of P fertilizer is taken up by crops in the first growing season after application (Zhang et al., 2007). Many previous studies have found that manure can be used as alternative P fertilizer, which can improve efficiency of inorganic fertilizers and enhance wheat productivity grown in alkaline calcareous soils (Cordell et al., 2009; Achat et al., 2014; Ikram et al., 2019a; Ikram et al., 2019b; Akhtar et al., 2020). Besides, a substantial part of applied P accumulates in the soil as so-called legacy P (Rowe et al., 2015). This legacy P in arable lands is estimated at a minimum of 347 kg P ha^{-1} within the 0–20 cm depth soil layer (Rowe et al., 2015). On the one hand, legacy P, as a potential P resource, may be absorbed by crops in subsequent growing seasons; on the other hand, excessive P accumulation in soil increases the risk of P loss into the environment through soil erosion and surface runoff (Stockdale et al., 2002; Bai et al., 2013; Zhang et al., 2019a; Zhang et al., 2019b). Sustainable utilization of legacy P is necessary to address this challenge (Rowe et al., 2015).

To achieve optimal P fertilizer application that ensures crop yield while reducing environmental risk, it is necessary to adjust P application rates by taking so-called legacy P from past applications into account. To do so, soil P models may be used as a tool by providing a platform to estimate soil P processes and crop uptake across cropping systems and growth conditions. The main models currently used include DPPS, EPIC (erosion-productivity impact calculator), DASST (decision support system for agrotechnology transfer), and APSIM (agricultural production simulation model) at the field and global scales, which have been reviewed by Das et al. (2019); Sattari et al. (2012); and Sattari et al. (2014). All of the above models face a common challenge in the initialization of conceptual soil P pools that are defined in models but cannot be directly measured and evaluated by regular chemical analysis. As a widely used model, DPPS has been used to reproduce historical crop P uptake as a function of P inputs from fertilizers and to estimate P requirements for crop production up to 2050 at the continental and global scales (Sattari et al., 2012). It is suggested that 20% of P fertilizer could be saved until 2050 by accounting for residual P in China (Sattari et al., 2014). The prediction of P demand by the DPPS model is based on accurately simulating long-term historical crop P uptake by year step. However, it cannot simulate crop P uptake by season. Additionally, it is not effective for soil P fertility simulation, which can be easily characterized by a measurable index, such as Olsen-P. In addition, the DPPS model does not consider the influence of soil type on crop P uptake. A further developed model is needed to overcome these shortcomings.

In this study, we developed a new model called the LePA (legacy phosphorus assessment) model based on the correlation between soil total P (TP), Olsen-P, and crop yield. It is an empirical model including three P pools and is able to estimate P demand according to various soil P states. To verify this model at a field scale, the objectives of this study are as follows: (1) to calibrate the LePA model using a dataset collected from two long-term fertilizer experiments, (2) to assess the simulation accuracy of the LePA model through a comparison with DPPS, and (3) to estimate the P fertilizer demand based on modeling in the next few decades.

MATERIALS AND METHODS

Study Site and Experimental Design

Two long-term fertilizer experiments were used to collect crop yield, soil TP, and Olsen-P data for LePA model development in this study. The first experiment, located in Yangling, Northwest China (34° 17′ N, 108° 00′ E), has been conducted since 1990. Soil physical and chemical properties at the beginning of the experiment are shown in **Table 1**. The cropping system in the experiment was a rotation of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.), with 11 treatments arranged in a randomized block design. Only three of these were selected to develop the LePA model, including (1) NP (nitrogen and P fertilizer application), (2) NPK (N, P, and potassium fertilizer application), and (3) NPKS (N, P, and K fertilizer application combined with straw return). In the field experiment, nutrients were applied, such as urea for N, calcium superphosphate for P, and potassium sulfate for K. All fertilizers were used as basal dressings. Straw incorporation (maize) was carried out only before the sowing of winter wheat. The amount of N, P, and K applied with straw each year is not included in the amount of fertilizer. The rates of nutrient application are shown in **Table 2**.

TABLE 1 | The initial soil properties in two long-term experiment sites (Yang and Qiyang).

Items	Units	Sites	
		Yangling	Qiyang
Soil classification in China		Loessial soil	Red earth
Soil classification in FAO		Calcaric Regosol	Eutric Cambisol
Beginning years		1990	1990
Soil organic matter	%	1.09	1.15
Total N	G N kg^{-1}	0.83	1.07
Total P	G P kg^{-1}	0.61	0.52
Total K	G K kg^{-1}	22.8	13.7
Alkaline hydrolysable N	Mg N kg^{-1}	61.3	79.0
Olsen-P	Mg P kg^{-1}	9.57	10.8
NH_4OAc-K	Mg K kg^{-1}	191	104
PH		8.62	5.70
Bulk density	g cm^{-3}	1.30	

TABLE 2 | Application rates of N, P, K, and straw at the two long-term experimental sites (Yangling and Qiyang).

Item	Yangling		Qiyang	
	Wheat	Maize	Wheat	Maize
Total N (kg ha^{-1} yr^{-1})	165	187	90	210
Fertilizer P (kg ha^{-1} yr^{-1})	58	25	16	37
Fertilizer K (kg ha^{-1} yr^{-1})	68	77	25	58
Straw (t ha^{-1} yr^{-1})	N equivalent		Half of the harvested straw	

The second experiment has been conducted at Qiyang, South China (26° 45′ N, 111° 52′ E), since 1990, with the same rotation system of winter wheat and summer maize. The experiment has 12 treatments arranged in a randomized block design, three of which were used for model development, which were the same as Yangling. Nutrients were applied, such as urea for N, calcium superphosphate for P, and potassium chloride for K. Half straw incorporation of the previous crop was carried out before sowing of the seasonal crops. The N, P, and K nutrients of straw returned to the field are not included in the total fertilization. **Tables 1** and **2** show detailed soil properties and the amount of nutrients applied for the treatments at this experimental site.

Soil Analysis and Data Collection

Soil samples were taken from the top 20 cm of soils after the maize was harvested each year. Five soil cores (5 cm diameter) were collected for each treatment each year. Soil samples were mixed thoroughly, air-dried, and crushed until they could pass through a 1 mm sieve for Olsen-P analysis and a 0.15 mm sieve for total P analysis. Olsen-P was extracted using 0.5 mol. L^{-1} $NaHCO_3$ (2.5 g soil, 50 ml solution, 25°C, shaken for 30 min), followed by the colorimetric measurement of inorganic phosphorus (Pi) using the molybdate-ascorbic acid method (Murphy and Riley, 1962). Total P was measured from H_2SO_4-$HClO_4$ digestion, using the molybdate-ascorbic acid method.

Data on crop yield, soil TP, and Olsen-P from the two long-term fertilizer experiments were collected from the published literature (Yang et al., 2009; Cai et al., 2011; Zhao et al., 2012; Yang et al., 2014; Xu et al., 2015; Khan et al., 2018; Yang et al., 2018; Li et al., 2019; Wu et al., 2020). The data reported as graphs in the original publications were extracted using GetData Graph Digitizer (version 2.25, developer: S. Fedorov). Harvested P was calculated as production × P content of the harvested product. The datasets are available in **Supplementary Tables S1–S3**.

Model Descriptions

The DPPS model, including two dynamic P pools, was used to simulate the long-term historical annual P uptake by crops for a time series of P inputs and to estimate the future P inputs for a specific future target P uptake (Wolf et al., 1987; Sattari et al., 2012). Phosphorus input for this model is the sum of P inputs (chemical fertilizers and manures), weathering, and atmospheric deposition. Crop P uptake and P loss are two outflows from the plant-soil system. The net P input (P input excluding runoff loss) is allocated to the labile (P_L; 80%) and stable pools (P_S; 20%).

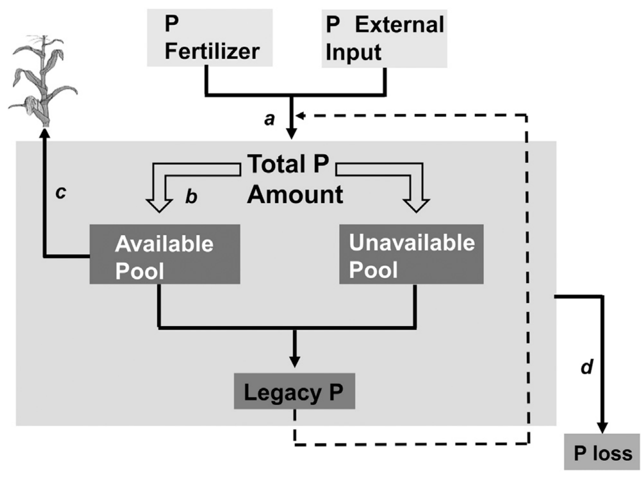

FIGURE 1 | Scheme of the LePA model. The model includes three phosphorus pools: the available (P_A) pool, the unavailable (P_U) pool, and the legacy P (P_{LE}) pool, comprising both organic and inorganic P. Two inputs of P to the system are defined: fertilizer and external input; the external input of P includes weathering and deposition. The coefficient *a* refers to the total P input (fertilizer and external input). The coefficient *b* refers to the fraction of soil total P amount (TPA) that transfers to the P_A. Coefficient *c* represents crop P uptake fraction from P_A. Parameter *d* is runoff loss from soil TPA.

These two phosphorus pools are mutually transformed every year. A detailed description and application of the model for estimating future P demand are shown in the study by Sattari et al. (2012) and Wolf et al. (1987).

The LePA model is a new model for assessing soil legacy P, which was developed for this study. In this model, P inputs include mineral fertilizer and external inputs (weathering and atmospheric depositions) and P outputs include crop P uptake and P loss. Unlike DPPS, three phosphorus pools are distinguished in this model, including the available pool (P_A), unavailable pool (P_U), and legacy P pool (P_{LE}). Among the three pools, P_A and P_U indicate P that can or cannot be absorbed by crops in the growing season, respectively, and P_{LE} indicates remaining P in P_A after being absorbed by crops and P in P_U. The sum of the three phosphorus pools is the soil total P amount (TPA) (**Figure 1**). Soil TPA in a given soil layer with a unit of kg ha^{-1} responds quantitatively to the budget between input and removal. The initial value of soil TPA (TPA_0) is calculated by the measured value of soil total P (TP_0) at the beginning of long-term fertilizer experiments, as shown in **Eq. 1**.

The LePA model in this study is developed according to the correlations between soil TP, Olsen-P, and crop yield of the long-term fertilizer experiments in Yangling and Qiyang (Bai et al., 2013). The empirical equations used in the LePA model are shown in **Table 3**. Soil TPA in the first year (TPA_1) is calculated by TPA_0, P inputs and P loss, as indicated in **Eq. 2**. Soil TP is calculated through the conversion relationship between it and soil TPA (**Eq. 1**). Soil Olsen-P is determined by the correlation between soil TP and Olsen-P. We assume that crops absorb all the phosphorus in P_A until soil Olsen-P reaches the critical level for crop production, which is 16.1 and 14.6 mg kg^{-1} for wheat

TABLE 3 | Principle equations used for LePA model operating of Yangling and Qiyang sites Bai et al. (2013).

Equation number	Equations	
	Yangling	Qiyang
Correlation between soil TP (x) and Olsen-P (y)		
1	y_1 = 93.1x-51.1, x < 1.32	y_1 = 3.5x+2.8, x < 0.51
2	y_2 = 257.6x-268.4, x > 1.32	y_2 = 152.8x-73.3, x ≥ 0.51
Correlation between soil Olsen-P (x) and crop yield (y)		
3 Wheat	y = 0.06x-0.5, x < 16.1	y = 0.04x+0.19, x < 12.7
4 Wheat	y = 0.90, x ≥ 16.1	y = 0.69, x ≥ 12.7
5 Maize	y = 0.05x+0.22, x < 14.6	y = 0.02x+0.22, x < 28.2
6 Maize	y = 0.90, x ≥ 14.6	y = 0.71, x ≥ 28.2

and maize in Yangling and 12.7 and 28.2 mg kg^{-1} for the two crops in Qiyang, respectively. The observed crop P uptake is therefore equal to the size of P_A during this period, which allows the determination of the correlation between soil TPA and P_A (**Supplemental Figure S1**). The remaining TPA, which is not allocated to P_A, is allocated to P_U. Excessive P_A, which cannot be absorbed by crops when soil Olsen is above the critical level, and P_U are transferred to $P_{LE.}$ The equation is used to calculate soil legacy P, as indicated in **Eq. 3**. Legacy P is then available for crop uptake in the following crop growing season. Thus, soil TPA_{n+1} is calculated by **Eq. 4**. The model will continue to run according to the above calculation principles season by season.

$$TPA_0\,(\mathrm{kg\,ha^{-1}}) = TP_0\,(\mathrm{g\,kg^{-1}}) \times 20\,(\mathrm{cm}) \times D_b\,(\mathrm{g\,cm^{-3}}) \times 10000, \quad (1)$$

$$TPA_1 = TPA_0 + a - d, \quad (2)$$

$$P_{LE1} = (TPA_0 + a - b - d) + b - c \quad (3)$$

$$TPA_{n+1} = P_{LEn} + a - d. \quad (4)$$

The coefficient D_b refers to soil bulk density. Coefficient a refers to the total P input. Coefficient b refers to the fraction of soil TPA that transfers to the P_A. Coefficient c represents crop P uptake from P_A. Parameter d is runoff loss from soil TPA.

Crop growth was severely limited at the Qiyang site when the soil pH was lower than 5.0 (**Supplemental Figure S2**). To simulate this effect of low soil pH on P uptake, we modified the LePA model according to empirical equations between soil pH and crop yield in acidic soil (**Supplemental Figure S3**).

In the LePA model, the global value used for the P supply from weathering is 1.6 Tg yr^{-1} and that from atmospheric deposition is 0.4 Tg yr^{-1} (Liu et al., 2008). The average P inputs per hectare are 1 and 0.25 kg ha^{-1} yr^{-1} from weathering and deposition, respectively, which are the same as for the DPPS model. When P loss is calculated by cultivated land area (MNR., 2016) and P loss in provinces (Zhang et al., 2019a), the P loss in northwest and south China is 0.36 and 1.34 kg P ha^{-1} yr^{-1}, respectively.

Calibration and Validation

For the DPPS model, observed crop P uptakes of the NPK treatment from 1990 to 2008 were used to calibrate the parameters, and the NP and NPKS treatments were used to validate the optimized parameters for the model. The LePA model was used to simulate the P uptake of wheat and maize and the soil TP and Olsen-P dynamics at the study sites. For LePA validation, the simulated data were compared with the observed data of crop P uptake, soil TP, and Olsen-P for the NP, NPK, and NPKS treatments from 1990 to 2008, where unseasonable values of observed soil TP were obvious within these datasets according to the P budget between P inputs and removals (**Supplementary Tables S4, S5**), and these values of observed soil TP were eliminated as outliers when less than 1/3 or more than 3 times the theoretical changes between two adjacent years were evident.

Statistical Analysis

We evaluated the performance of the DPPS and LePA models by comparing the simulated and observed values, including the total P uptake of crops for the DPPS model and the P uptake of wheat and maize, soil total P, and Olsen-P for the LePA model. The coefficient of determination (R^2) and root mean squared error (RMSE) between simulated and observed values were used to evaluate the model performance. The higher the R^2 is, the closer the slope is to 1.0, and the lower the RMSE and intercept are, the better the model performance is. All statistical analyses were performed with Microsoft Excel (version 2016, Microsoft Corporation, Redmond, Washington, USA).

$$R^2 = \frac{\sum (S_i - \overline{O}_i)^2}{\sum (O_i - \overline{O}_i)^2}, \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}}, \quad (6)$$

where O_i and S_i are the observed and simulated values, respectively.

RESULT

Crop P Uptakes Simulated by the DPPS and LePA Models

Crop P uptakes simulated by DPPS in the NP, NPK, and NPKS treatments are shown in **Figure 2** and **Table 4**. For Yangling, the R^2 was 0.28, and the RMSE was 6.87 for calibration between simulated and observed crop P uptakes (n = 18, $p < 0.05$). These values were 0.23 and 7.39 (n = 36, $p < 0.01$) for validation, respectively. In contrast, crop P uptake was only accurately

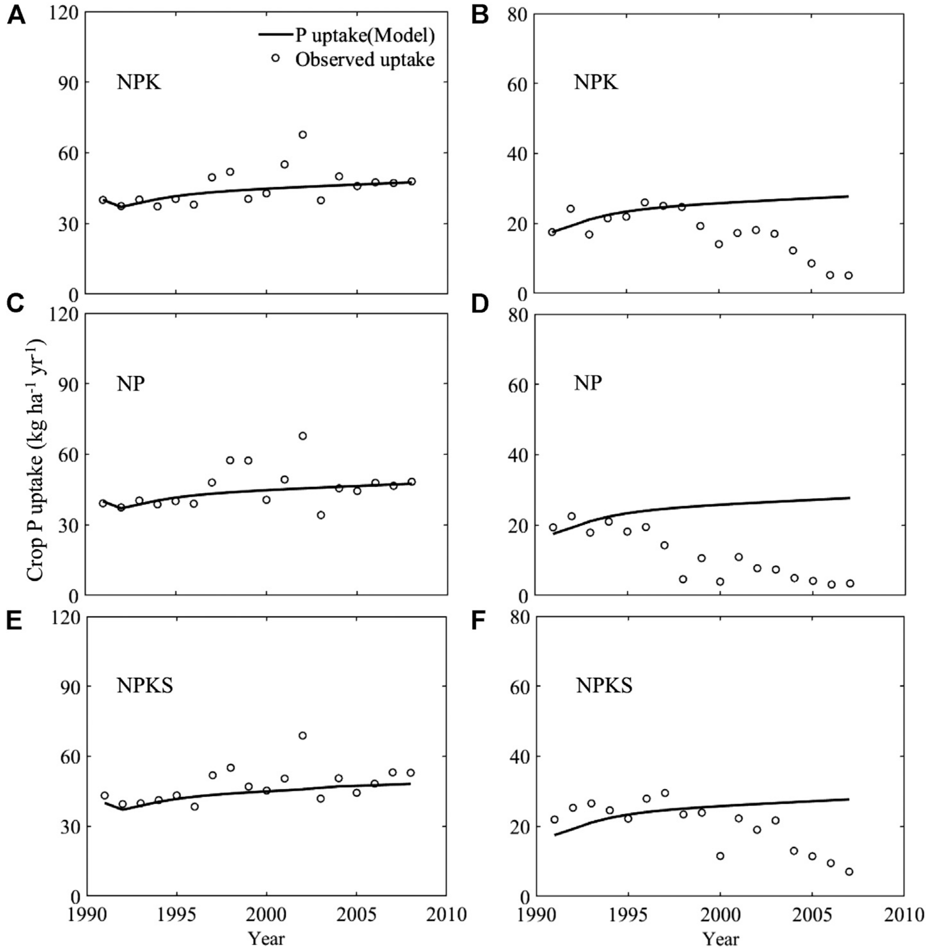

FIGURE 2 | Simulated and observed total P uptake of crops by the DPPS model at Yangling site (1991–2008) **(A and C, E)** and Qiyang site (1991–2007) **(B and D, F)**. Crop P uptake of wheat and maize in the NPK treatment was used for calibration. Crop P uptake of wheat and maize in the NP and NPKS treatments was used for validation.

TABLE 4 | Statistical analysis of DPPS model performance on crop P uptake in Yangling and Qiyang sites.

Criteria	Yangling		Qiyang	
	Calibration[a]	Validation[b]	Calibration[c]	Validation[c]
R^2	0.28	0.23		
RMSE	6.87	7.39		
Number of samples	18	36	17	34

[a]Crop P uptake in the NPK treatment was used for calibration.
[b]Crop P uptake in NP and NPKS treatments was used for validation.
[c]The DPPS model was failed to simulate crop P uptake in Qiyang.

simulated in NP, NPK, and NPKS at the beginning of the experiment in Qiyang by the DPPS model and was overestimated since 1999 in NPK, 1995 in NP, and 2000 in NPKS (**Figure 2**).

Crop P uptake simulated by LePA in the same three treatments is shown in **Figure 3** and **Figure 4**. The R^2 of validation between simulated and observed wheat P uptake in Yangling (n = 54, $p <$ 0.01) was 0.28 with an RMSE of 4.77 and was much higher than that of maize (R^2 = 0.02; RMSE = 4.56) (**Table 5**). A large variation in maize yield resulted in the poor fitting of the LePA model. As with the DPPS model, the original LePA model failed to simulate crop P uptake in Qiyang, as shown in **Figure 4**. To solve this problem, we modified the LePA model according to the empirical equation between soil pH and crop yield in acidic soil (**Supplemental Figure S3**). After modification, the simulation accuracies of the LePA model were much improved in all treatments, and the R^2 of the modified modeled and observed P uptake increased to 0.70 for winter wheat and 0.70 for summer maize (n = 51, $p < 0.01$).

Soil TP and Olsen-P Simulated by the LePA Model

The R^2, RMSE, and regression equations of the soil TP and Olsen-P simulations by the LePA model are shown in **Figure 5**. For Yangling, LePA could explain 82% of the variation in observed total P and 70% of the variation in Olsen-P (**Figure 5A C**). The

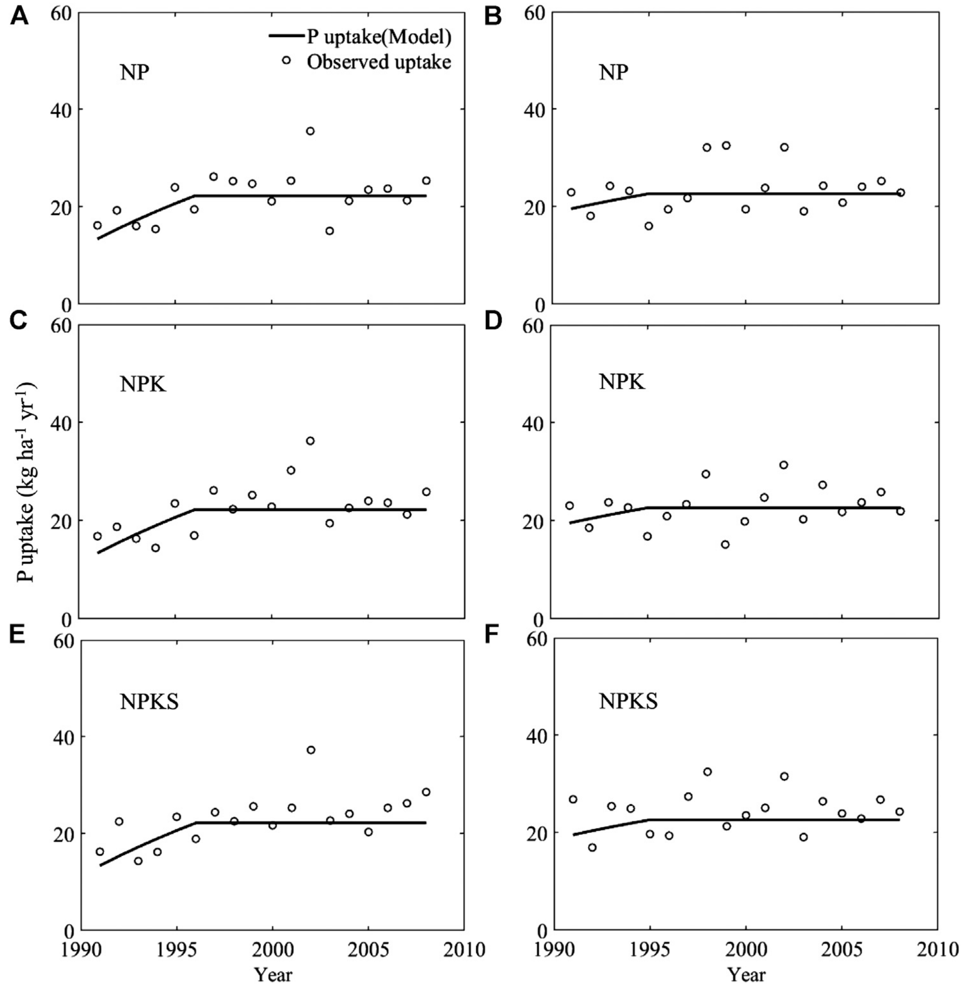

FIGURE 3 | Simulated and observed P uptake of wheat **(A and C, E)** and maize **(B and D, F)** by the LePA model in the NP, NPK, and NPKS treatments at Yangling site (1991–2008).

regression lines are close to the 1:1 lines. The R^2 was 0.90, and the RMSE was 0.07 between the original simulated and observed soil TP in Qiyang (**Figure 5B D**), and the values were 0.58 and 8.37 for soil Olsen-P, respectively. After modification, the model showed a better fit than the original simulations with lower RMSE, and the regression lines were closer to the 1:1 lines.

P Fertilizer Demand Estimated by the DPPS and LePA Models

For our model predictions up to 2080, we determined 45 kg P ha^{-1} yr^{-1} as the target crop P uptake to achieve the highest yield. Crop P uptake and P fertilizer demand simulated by DPPS in the NPK treatment of Yangling from 2009 to 2080 are shown in **Figure 6A**. The application of P fertilizer at a rate of 51 kg P ha^{-1} yr^{-1} is needed to maintain target crop P uptake during this period. Labile and stable pools simulated by DPPS showed a continuous increase from 1991 to 2008 with P application (**Figure 6B**). This result indicated that P application in excess of P demand caused an accumulation of soil P. Crop P uptake and the labile pool were reduced from 48 to 44 kg P ha^{-1} yr^{-1} and 534 to 480 kg P ha^{-1} yr^{-1} in the first eight years, respectively, and maintained at this level if P application was reduced to 51 kg P ha^{-1} yr^{-1} since 2009. The results showed that P fertilizer application might be reduced by 38% when the replenishment of soil residual P to labile P was considered. As discussed above, the DPPS model showed a large error when carrying out a scenario analysis of crop P uptake and soil P change in low pH soil in Qiyang (**Figure 6C, D**).

The scenario analysis of crop P uptake in the NPK treatment in Yangling by LePA from 2009 to 2080 is shown in **Figure 7A**. Crop P uptake remained stable at 45 kg P ha^{-1} yr^{-1} when P fertilizer application was reduced from 82 to 39 kg P ha^{-1} yr^{-1}. P fertilizer application can therefore be reduced by 52% compared with the conventional application rate during this period, which also reveals the crucial impact of residual P for China at the field scale. Soil Olsen-P decreased from 32 mg kg^{-1} to 20 mg kg^{-1} during this period (**Figure 7B**). At the same time, both

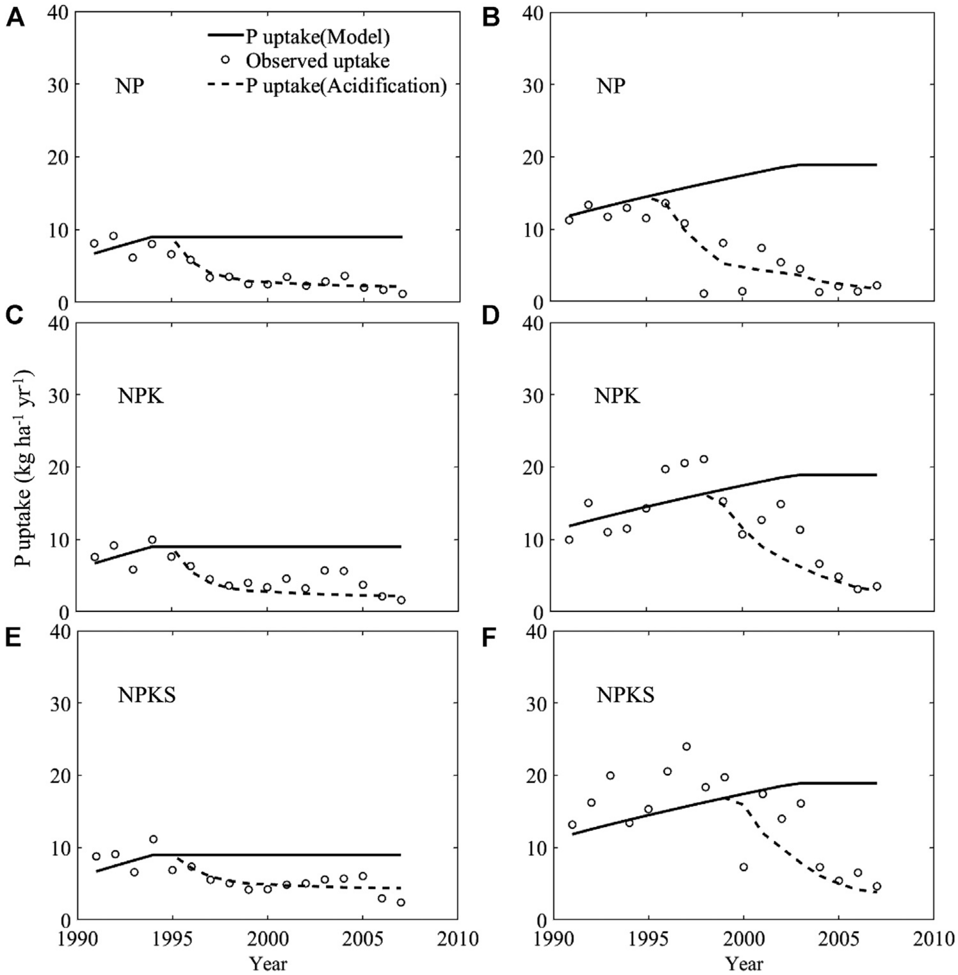

FIGURE 4 | Simulated and observed P uptake of wheat **(A and C, E)** and maize **(B and D, F)** by the LePA model in the NP, NPK, and NPKS treatments at Qiyang site (1991–2007). The solid and dotted lines represent the original and modified simulated crop P uptake, respectively.

TABLE 5 | Statistical analysis of LePA model performance on crop P uptake in Yangling and Qiyang sites.

Criteria	Yangling[a]			Qiyang[b]		
	Wheat	Maize	Total	Wheat	Maize	Total
R^2	0.28	0.02	0.19	0.70	0.70	0.74
RMSE	4.77	4.56	7.85	1.37	3.55	4.11
Number of samples	54	54	54	51	51	51

[a]*Correlation between simulated and observed crop P uptake in the NP, NPK, and NPKS treatments from 1991 to 2008 in Yangling.*
[b]*Correlation between simulated and observed crop P uptake in the NP, NPK, and NPKS treatments from 1991 to 2007 in Qiyang. The original LePA model was failed to simulate crop P uptake in three treatments, whereas the modified LePA model could simulate it accurately.*

available and unavailable pools showed a significant decrease from 31 to 25 kg P ha^{-1} yr^{-1} and 2,293 to 1957 kg P ha^{-1} yr^{-1}, respectively (**Figure 7C**). Due to continuous P fertilizer application, legacy soil P in the NPK treatment reached 2,306 kg P ha^{-1} yr^{-1} in 2008, which was 140% of the beginning level in 1991 (**Figure 7D**). In the scenario mentioned above, legacy soil P was gradually depleted to 1960 kg P ha^{-1} yr^{-1} in 2080. Crop P uptake in the NPK treatment in Qiyang simulated by both the original and modified LePA models is shown in **Figure 8A**. Crop P uptake simulated by the original model was maintained at 28 kg P ha^{-1} yr^{-1} when P fertilizer application decreased from 52 to 28 kg P ha^{-1} yr^{-1} since 2008, which was much higher than that of the modified simulation. This revealed P that fertilizer application could be reduced by 46% compared with conventional application rates during this period. With P fertilizer application at a rate of 52 kg P ha^{-1} yr^{-1} from 1991 to 2007, the soil Olsen-P simulated by modified LePA gradually increased to 44 mg kg^{-1} (**Figure 8B**). The available and unavailable pools reached 25 and 1967 kg P ha^{-1} yr^{-1}, respectively (**Figure 8C**). Legacy soil P increased from 1,386 to 1988 kg P ha^{-1} yr^{-1} (**Figure 8D**). Due to low crop P uptake in acidic soils, soil Olsen-P, legacy P, and two phosphorus pools

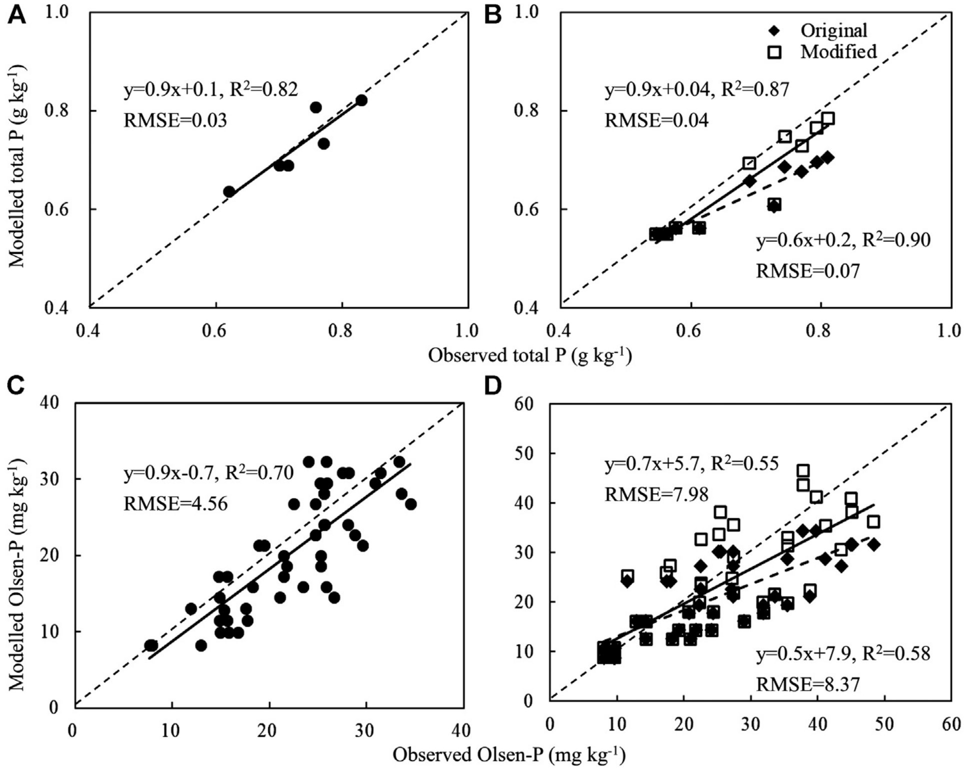

FIGURE 5 | Correlations of modeled and observed soil total P and Olsen-P in the NP, NPK, and NPKS treatments of Yangling **(A and C)** and Qiyang **(B and D)**. The gray dashed lines were the 1:1 lines.

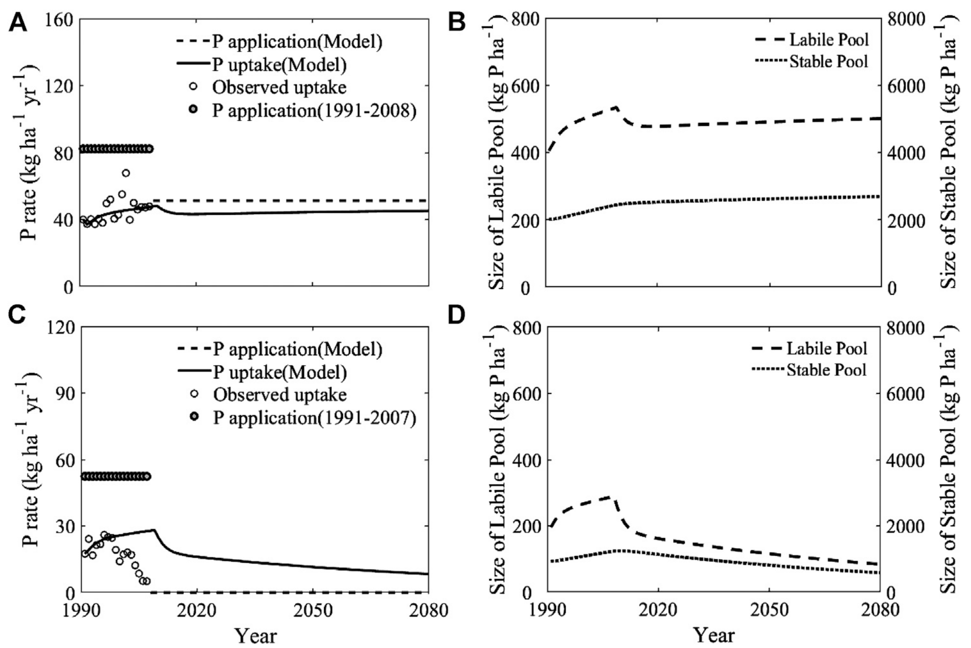

FIGURE 6 | Trends of annual P application and P uptake and labile and stable pools for the NPK treatment in the long-term positioning experiment of Yangling **(A and B)** and Qiyang **(C and D)** simulated by the DPPS model for the period of 1991–2080.

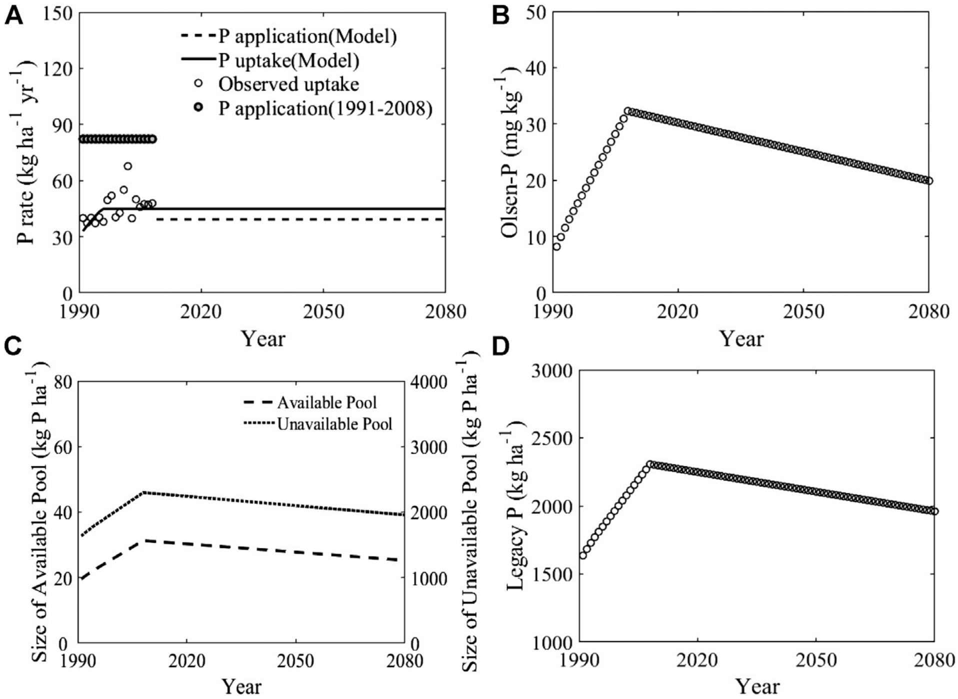

FIGURE 7 | Trends of annual P application and P uptake **(A)**, soil Olsen-P **(B)**, available and unavailable pool **(C)**, and legacy P **(D)** for the NPK treatment in the long-term positioning experiment of Yangling simulated by the LePA model for the period of 1991–2080.

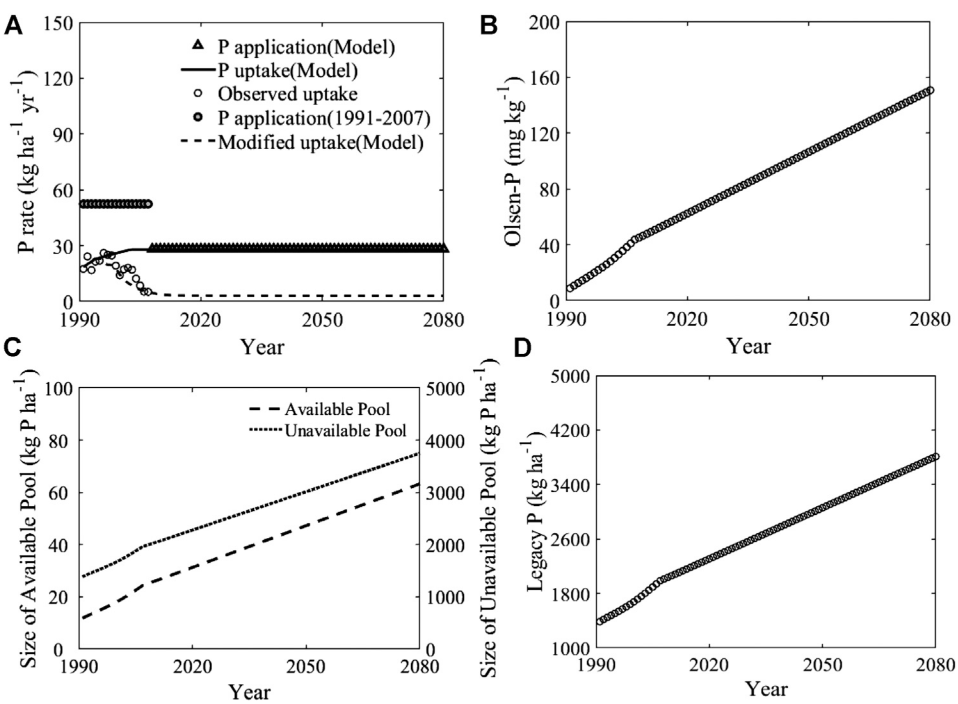

FIGURE 8 | Trends of annual P application and P uptake **(A)**, soil Olsen-P **(B)**, available and unavailable pool **(C)**, and legacy P **(D)** for the NPK treatment in the long-term fertilizer experiment of Qiyang simulated by the LePA model for the period of 1991–2080.

gradually increased with a P application rate of 28 kg P ha^{-1} yr^{-1} during the period of 2008–2080, reaching 151 mg kg^{-1}, 3,811, 63 (P_A), and 3,750 (P_U) kg P ha^{-1} yr^{-1} in 2080, respectively.

DISCUSSION

Two Model Performance on Crop P Uptake

The LePA model can better simulate the P uptake of wheat and maize in Yangling. It can be modified based on empirical equations according to special soil conditions. Crop P uptake could therefore be simulated well by modified LePA in low pH soil in Qiyang. LePA achieves higher flexibility for special crop-soil systems. In this study, DPPS did not fit annual crop P uptake very well, as shown in previous studies (Janssen et al., 1987; Sattari et al., 2012; Sattari et al., 2014). This might be because the DPPS model was more suitable for simulating a much longer-term historical crop P uptake. In addition, the large variation in crop yield caused by weather conditions among years also affects the accuracy of the simulation. The DPPS model failed to simulate crop P uptake in Qiyang. This was due to significant soil acidification in the NP, NPK, and NPKS treatments, where soil pH decreased below 5.0 since 1995 (**Supplemental Figure S2**). Soil acidification in Qiyang has significantly limited crop growth and P uptake, which has been mentioned by Cai et al. (2011). As the DPPS model did not consider this situation in the current version, it does not fit crop P uptake well in low pH soil.

LePA Model Performance on Soil TP and Olsen-P

A good simulation of soil TP and Olsen-P for Yangling and Qiyang by the LePA model indicates that LePA is a reliable tool for soil P fertility simulation. This is a new function compared with the DPPS model. Most models include available P, non- or low available P, and organic P with varying degrees of stability (Das et al., 2019). However, quantifying these pools is costly and time consuming. The LePA model solved the difficulty of initializing the soil P pools and evaluating them using measured soil P indexes compared with other widely used P models, such as DPPS, EPIC, DASST, and APSIM (Jones et al., 1984; Wolf et al., 1987; Daroub et al., 2003; Probert, 2004). Some researchers also found that the Olsen method is a good indicator of plant-available P and that P was the principal soil factor controlling growth (Poulton et al., 2013). Therefore, the LePA model might be an effective tool to monitor changes in plant-available P with time and guide soil P management under various soil P statuses.

Estimation of Future P Demand

Our estimate of the P fertilizer demand by LePA in Yangling is 39 kg P ha^{-1} yr^{-1} without yield loss for the period of 2009–2080. It is much lower than the conventional application rate (82 kg P ha^{-1} yr^{-1}) without accounting for legacy soil P. The DPPS model also showed lower projections of P demand up to 2080 in Yangling. Sattari et al. (2012) and Sattari et al. (2014) found that crop P uptake still continuously increases even after reducing P application slowly if soil residual P is large enough, which can be achieved by long-term P application. However, in the DPPS model, crop P uptake and the labile pool in Yangling decreased in the first few years if P application was directly reduced. This may be because 80% of the P fertilizer in the first growth season is assumed to transfer into the labile pool in the DPPS model, and the soil labile pool and crop P uptake are sensitive to changes in P application. This was inconsistent with experimental data at the field, farm, and county scales showing that crop yields could remain or increase for several years with decreasing or even omitting P application when soil-available P was adequate (Kamprath, 1967; van Keulen et al., 2000; Mishima et al., 2009; Verloop et al., 2010; Rowe et al., 2015). This result indicated that the LePA model was more efficient than DPPS in predicting the response of crop P uptake to P inputs under certain conditions. The soil Olsen-P simulated by LePA is 20 mg kg^{-1} in 2080, which still meets the recommended level for crop production in Northwest China (Li et al., 2015). The reduction trend in P application has been confirmed with the conceptual model of Li et al. (2011). When soil-available P (Olsen-P) is sufficient, only low rates of P fertilizer application are needed to maintain crop yields. The results indicate that legacy soil P can contribute to crop production with a considerable lag time. However, when soil legacy P was depleted to the critical level below which crop P uptake was limited, the same amount of P fertilizer representing the sum of crop P removal and runoff losses was needed to maintain soil P fertility, as also mentioned by Sattari et al. (2012).

Our results show that soil Olsen-P, legacy P, and two phosphorus pools simulated by modified LePA greatly increased due to low crop P uptake during the period of 2008–2080 in acidic soil in Qiyang. Soil Olsen-P is much higher than the critical level for P leaching potential in 2080, which is 78.2 mg kg^{-1} in southern China (Li et al., 2015). However, many studies have found that high-P soils often lead to serious environmental issues, especially in areas with high precipitation (Stockdale et al., 2002; Zhang et al., 2019b). Thus, improving soil pH to reach high crop P uptake should be considered with urgency in Qiyang.

CONCLUSION

To synthesize the major outcomes of this study, the novel LePA model is a useful tool for guiding soil P management from the field to country scales. It can be developed according to several empirical equations derived from long-term experiments and estimates the future P demand for areas with similar cropping systems and soil types. Biological processes related to soil P mobilization in field practices are not considered in the current version, such as manipulating cropping systems, rhizosphere regulation, and microbial engineering. Thus, the LePA model needs to be further improved in the future to match the increasing requirements of environmentally friendly agriculture.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WY developed the new LePA model, analyzed the data and wrote the manuscript. GL provided the DPPS model and wrote the manuscript. TH revised the manuscript. MX and XY collected data for analysis. HL designed the study and revised the manuscript. JZ and JS offered the suggestion.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.621833/full#supplementary-material.

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Conflict of Interest: Author GL was employed by the company Israel Chemicals Ltd (ICL).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.