



Modeling Long-Term Impacts of Phosphorus Fertilization Strategies on Maize Productivity and Soil P Dynamics in Calcareous Soils of North China Plain

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The North China Plain (NCP), a major maize production region in China, faces critical challenges of P overuse under intensive farming, leading to soil P accumulation, leaching risks, and threats to groundwater quality and P resource sustainability. This study employed a parameter-calibrated APSIM model (v7.9) to simulate long-term effects (2007–2017) of eight P application rates (0–300 kg P₂O₅ ha⁻¹) on maize growth, P utilization, and soil P dynamics using field trial data from Quzhou County (36.9°N, 115.0°E), Hebei Province, China. Results demonstrated that 71 kg P₂O₅ ha⁻¹ optimized maize productivity, achieving mean aboveground biomass and grain yields of 17.5 t ha⁻¹ and 9.3 t ha⁻¹, respectively, with a P use efficiency (PUE) of 17%. Continuous P fertilization induced progressive accumulation of labile P (32 mg/kg under 75 kg P₂O₅ ha⁻¹ application rate vs. 40.8 mg/kg under 100 kg P₂O₅ ha⁻¹ application rate in 2017) and stable inorganic P pools, with P100 exceeding the environmental threshold (39.9 mg/kg) for calcareous soils. Post-cessation simulations (22 years) revealed that legacy P from 11-year P75 applications sustained maize yields at 8–10 t ha⁻¹ for 12–13 years, despite labile P decreasing from 32.3 to 15.8 mg/kg. Model analysis highlighted limitations in APSIM's current P module, which prioritizes adsorption-desorption over precipitation-dissolution mechanisms critical for calcareous soils. These findings provide a theoretical foundation for P reduction strategies in NCP maize systems.

Keywords: maize, phosphorus, North China Plain, scenario analysis, APSIM

INTRODUCTION

Global yields of the three major cereal crops—wheat, rice, and maize—have increased greatly over the past 5 decades: wheat and rice have tripled and maize increased fivefold (Soto-Gómez and Pérez Rodríguez, 2022). However, the consumption rate of chemical phosphorus (P) fertilizers has far outpaced these yield gains (IFA, 2016), creating dual challenges of environmental pollution risks and unsustainable financial burdens for farmers, while exacerbating P resource depletion (Aulakh et al.,

2007; Bai et al., 2013; Gong et al., 2025). Global P demand continues to escalate, with production projected to peak within decades, drawing international concern due to P non-renewable nature (Cordell et al., 2009; Gilbert, 2009; Shen et al., 2011). This critical situation underscores the urgent need to establish scientifically sound P application strategies within intensive agricultural systems to balance productivity enhancement with resource conservation and environmental protection.

P management is fundamental to sustainable farmland ecosystems, directly influencing both agricultural productivity and environmental impacts (Mathot et al., 2020). In the North China Plain, maize stands as a primary grain crop. In recent years, maize yields under intensive cultivation have shown a steady increase. However, the high P fertilizer inputs required for such production have led to significant accumulation and leaching of soil P nutrients, posing severe threats to groundwater environments. Furthermore, P is a key contributor to water eutrophication, with P loss from agricultural soils closely linked to water pollution (Zhang et al., 2019). As a non-renewable mineral resource, P faces critical challenges: China's current phosphate reserves are insufficient to meet economic development demands, and global phosphate resources are projected to be depleted in the near future (Cordell et al., 2009). Compounding this issue, most P fertilizer applied to soils is converted into slowly available or unavailable forms, with only a small fraction remaining as soluble available P (Zhou et al., 2010). Consequently, reducing P inputs while optimizing application rates has emerged as a critical consideration in farmland management strategies.

Maintaining rational P application rates and enhancing the utilization efficiency of residual soil P enables significant reductions in fertilizer inputs while improving P use efficiency (Zhang et al., 2019). Optimal P application rates are fundamentally determined by crop-specific P requirements, which exhibit substantial interspecies variability. In the context of global phosphate rock scarcity, residual soil P defined as the net balance between cumulative P inputs and outputs—represents an underutilized reservoir capable of meeting crop demands across multiple growing seasons (Gong et al., 2023; Sattari et al., 2012). The availability of this legacy P pool is governed by soil P adsorption capacity, pH dynamics, crop species selection, and temporal patterns of fertilizer management (Sanchez, 2019). Furthermore, the immobilization of phosphate ions through adsorption processes with soil Ca^{2+} and precipitation reactions with Fe/Al oxides substantially reduces both newly applied and residual P bioavailability (Wang et al., 2014). Developing robust models to elucidate P dynamics in soil-crop systems necessitates comprehensive long-term field experimental data on maize growth responses to varied P supply regimes. However, acquiring region-specific, soil-type-dependent, and crop-varied P response datasets remains prohibitively time-intensive. In this context, system-level soil-crop models offer a powerful computational framework to simulate crop growth patterns and nutrient cycling processes with predictive accuracy.

Water and fertilizer management practices represent the most effective and commonly used regulatory approaches in agricultural production. Extensive experimental evidence

demonstrates that P distribution across various processes can be actively modulated through farmland management measures. In recent years, research on P management and regulation in farmlands has increased significantly, with numerous studies focusing on the North China Plain (Guan et al., 2024; Li et al., 2021; Jiao, 2016). However, these studies predominantly rely on empirical equations or static experiments to determine management strategies (Wang, 2009), often neglecting the impacts of climate change and soil characteristics while lacking long-term monitoring and evaluation of regulatory measures.

The Agricultural Production Systems Simulator (APSIM) has emerged as a globally recognized modeling platform for simulating crop growth dynamics, yield formation, and resource use efficiency across major cereal crops (maize, wheat, rice) and intensive cropping systems (wheat-maize and wheat-rice rotations). Its robust architecture enables comprehensive analysis of agricultural systems under variable environmental and management conditions, particularly in response to dynamic climatic patterns and agronomic interventions such as water management and nitrogen fertilization (Chen et al., 2010; Hochman et al., 2009; Lai et al., 2025; Verburg et al., 2025; Wang et al., 2012). The APSIM framework incorporates a specialized SoilP module specifically designed to simulate P dynamics in agricultural soils. This module mechanistically represents fundamental soil processes governing P availability, including adsorption-desorption equilibrium and fertilizer-soil interactions, providing critical insights for optimizing P management strategies (Delve et al., 2009). Empirical validation studies have demonstrated the module's capability to accurately predict crop responses to P fertilization, particularly in P-fixing soils where adsorption-desorption mechanisms dominate soil P dynamics (Shen et al., 2011). The module's process-based algorithms enable researchers to evaluate both short-term fertilizer effects and long-term P cycling in diverse agroecosystems. Our previous study had established a set of parameters regarding to the maizeP and soilP modules, and the parameterized APSIM module could predict the response of the crop yield to soil P dynamics within seasons on calcareous soils in NCP (Zhang et al., 2024).

Our study integrates field trial data from the Quzhou region with modeling approaches to investigate the long-term effects of P fertilizer management on maize growth, resource use efficiency, and soil P pool dynamics in the North China Plain. Through scenario analysis, we assess the comprehensive long-term impacts of P management practices and propose optimized strategies. The findings aim to provide both theoretical foundations and practical guidance for achieving high-yield and high-efficiency maize production.

MATERIALS AND METHODS

Initial Soil Properties and Model Settings

The model simulation was conducted for Quzhou Experimental Station of China Agricultural University (36.9°N, 115.0°E) in Hebei Province, China, covering the period from 2007 to

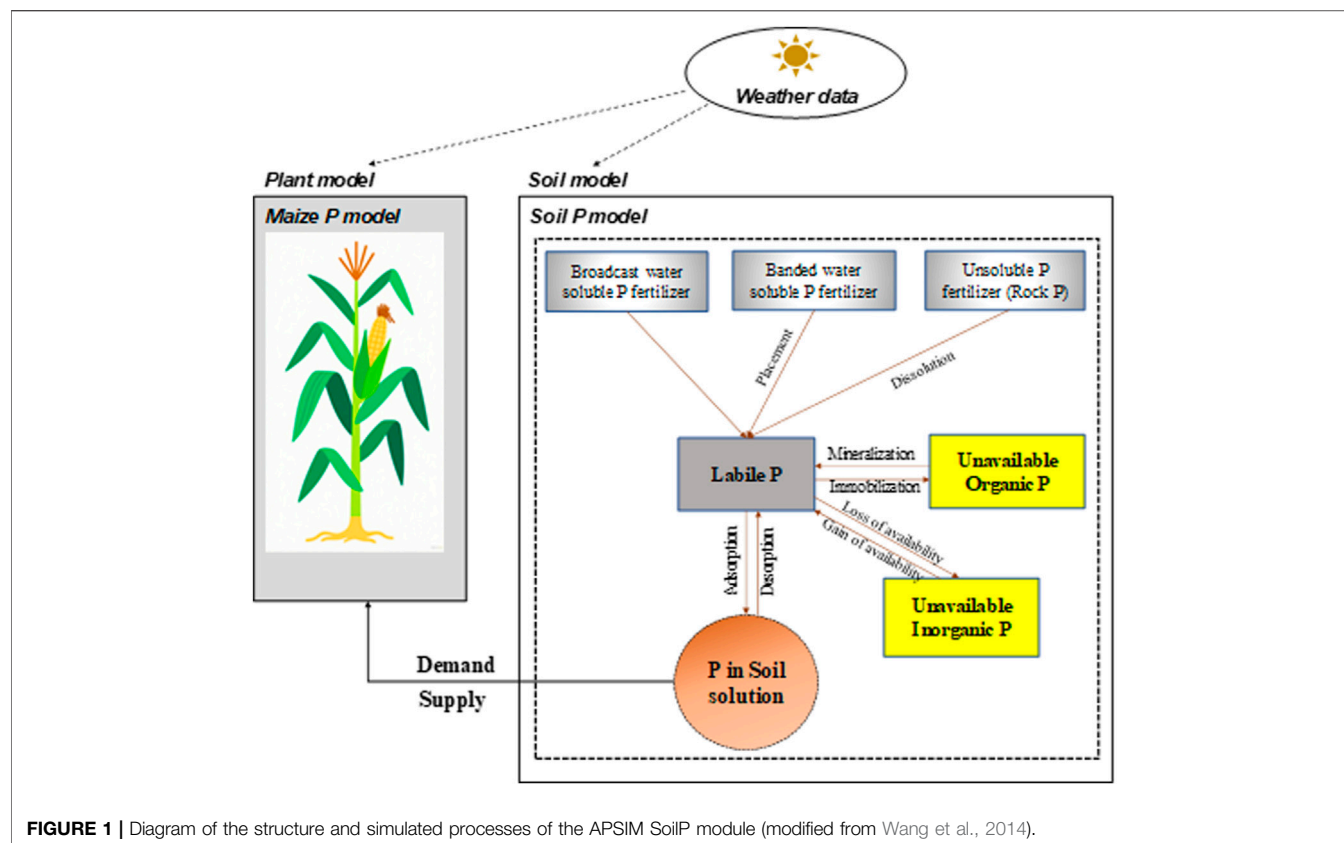


TABLE 1 | Maize cultivar, LAI and soil P parameters used in the simulation (Zhang et al., 2024).

Cultivar parameters		ZD958	
Head grain no max (maximum grain number per head)		900	
Grain gth rate (grain-filling rate (mg/grain/day))		5	
tt emerge to end juv (thermal time from emergence to the end of the juvenile stage (°C-d))		240	
tt flower to maturity (thermal time from flowering to maturity (°C-d))		900	
tt flower to start grain (thermal time from flowering to the start of the grain-filling stage (°C-d))		120	
Photoperiod slope		21	
LAI parameters		Original APSIM	Modified APSIM
leaf_no_dead_const (coefficient for the leaf senescence rate following flowering)		-0.025	-0.005
leaf_no_dead_slope		0.00035	0.00025
partition_rate_leaf (coefficient of the sigmoidal function between the leaf partition fraction and internode number)		0.0182	0.006
Soil P parameters		Original APSIM	Modified APSIM
a in the Freundlich isotherm		50	100
b in the Freundlich isotherm		0.7	0.75
Rate of P availability gain/loss		0.3	0.90

2017. The experimental site, which located in the core agricultural region of the North China Plain, features calcareous fluvo-aquic soil, and the top 20-cm soil layer exhibited a loamy-silty texture comprising 14.7% clay, 74.0% silt, and 11.3% sand. The chemical properties of the soil at the start of APSIM simulation in 2006 were as follows: soil pH (1:2.5 w/v H₂O) measuring 8.7, extracted mineral N (N_{min}) 19.8 mg kg⁻¹, labile P 6.6 mg kg⁻¹, and organic matter content 10.7 g kg⁻¹, respectively. Daily climate data from 2007 to 2017 including daily maximum and minimum temperature, rainfall, and sunshine hours were obtained from the weather station of Quzhou County. Daily solar radiation was calculated with daily sunshine hours using the Angstrom equations (Angstrom, 1924).

The management practices implemented in the APSIM model precisely replicated those applied in the field experiments from 2016 to 2017. Both the simulation period (2007–2017 and field experiment (2016–2017) were single-season maize cultivation. The maize cultivar Zhengdan 958 (ZD 958) was sown on May 26 at a final planting density was 75,000 plants ha⁻¹ with 60 cm row spacing of. All treatments were received with 225 kg N ha⁻¹ as urea, 60 kg K₂O ha⁻¹, and P fertilizer as calcium superphosphate. P and potassium were broadcast and incorporated into 0–20 cm soil before sowing. Urea was

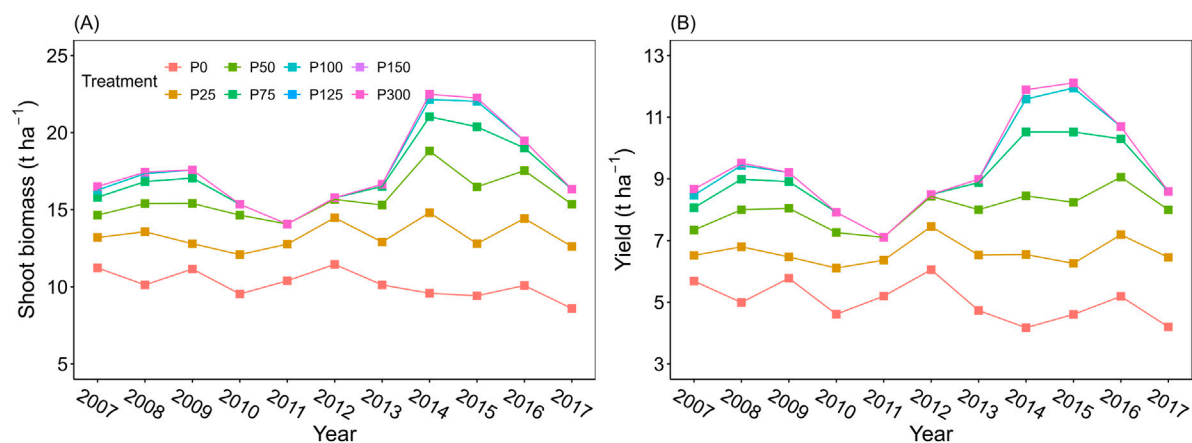


FIGURE 2 | Modeling of the effects of different P application rates on the dynamic changes of maize shoot biomass (A) and yield (B) simulated by the revised APSIM v7.9 model from 2007 to 2017.

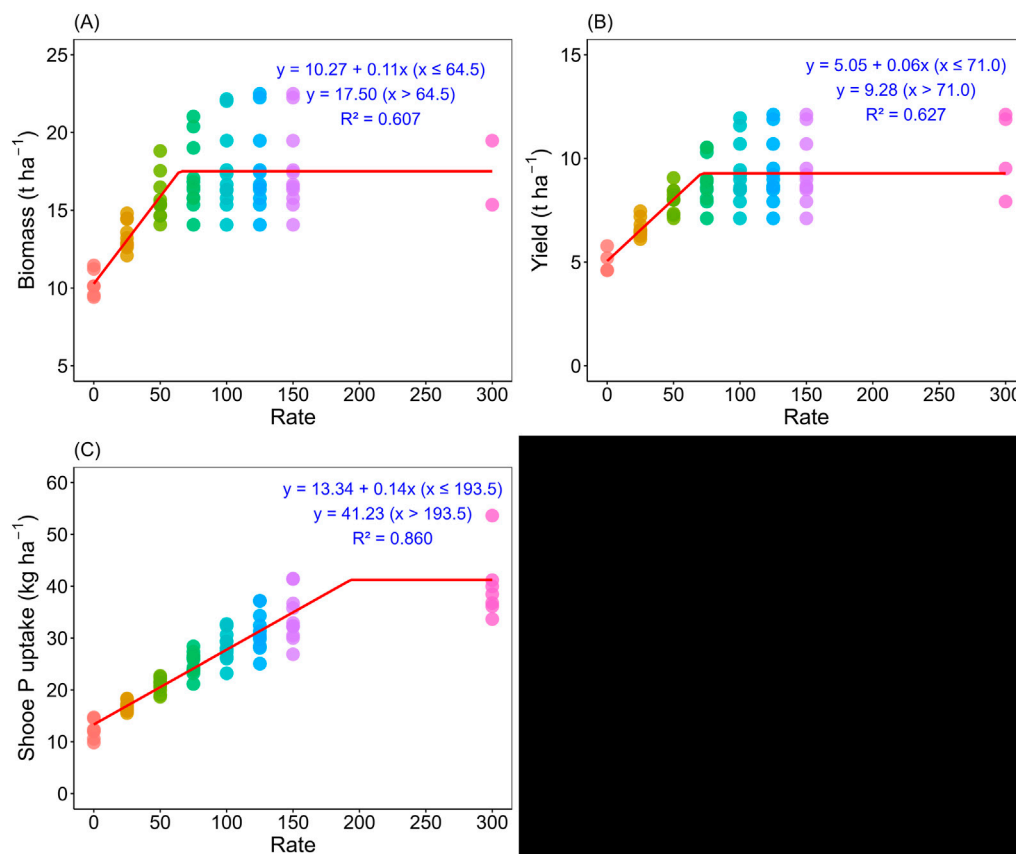


FIGURE 3 | Effects of different P applications on maize aboveground biomass (A), yield (B), and aboveground P uptake (C) simulated by the revised APSIM v7.9 model from 2007 to 2017.

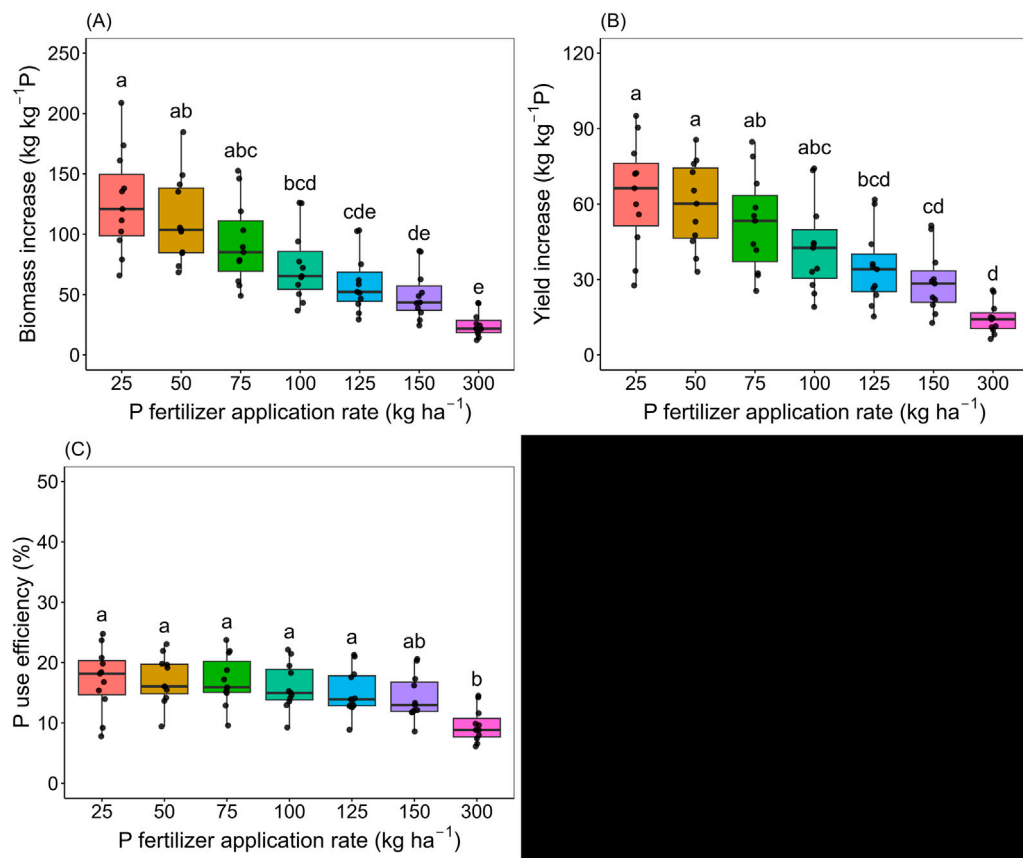


FIGURE 4 | Effects of different P application rates on maize biomass increase **(A)**, yield increase **(B)**, and PUE **(C)** simulated by the revised APSIM v7.9 model from 2007 to 2017. The box plots display the minimum, maximum, and the 10, 25, 50, 75, 90 and 100 percentiles.

applied in three applications during whole maize growth stage: 90 kg N ha⁻¹ at sowing, 60 kg N ha⁻¹ at the six-leaf stage, and 75 kg N ha⁻¹ at the 12-leaf stage. The automatic-irrigation switch was turned on to avoid water stress throughout the simulations.

APSIM Model Parameterization and Validation

The APSIM model version 7.9 was used to simulate above-ground biomass, grain yield, and P use efficiency of maize at the study site. In APSIM, phenological development of maize from emergence towards maturity is driven by the accumulation of thermal time. Above-ground biomass is simulated with the intercepted radiation.

The APSIM model has demonstrated capability in simulating maize above-ground biomass, crop yield, and nitrogen/phosphorus use efficiencies (Lai et al., 2025; Wang et al., 2014; Liu et al., 2012). Validation studies by Chen et al. (2010), Liu et al. (2012), Wang et al. (2012), Zhang et al. (2012), and Wang (2009) confirmed the model's robust performance in simulating maize growth dynamics in the North China Plain and Northeast China,

particularly regarding dry matter accumulation, yield formation, and nutrient uptake responses to nitrogen/phosphorus supply. Notably, Chen et al. (2010) identified systematic underestimation of above-ground biomass and yield in North China Plain simulations. This limitation was addressed by modifying the radiation use efficiency (RUE) parameter from its default value of 1.6 g/MJ to 1.8 g/MJ, based on methodologies established by Bastiaanssen and Ali (2003) and Tao et al. (2005), resulting in significantly improved biomass and yield predictions.

Within the APSIM framework, maize phenological progression from emergence to physiological maturity is governed by thermal time accumulation. Above-ground biomass production is determined by the interaction between canopy light interception and RUE across developmental stages, while P uptake dynamics are regulated by organ-specific P concentration thresholds during critical growth phases. The APSIM model, incorporating both the maize module and the soil P module (Figure 1), was calibrated using field experiment data (2016–2017) from Quzhou County, Hebei Province, China. Subsequently, the model was validated with data published in the literature, which was also sourced from the same site

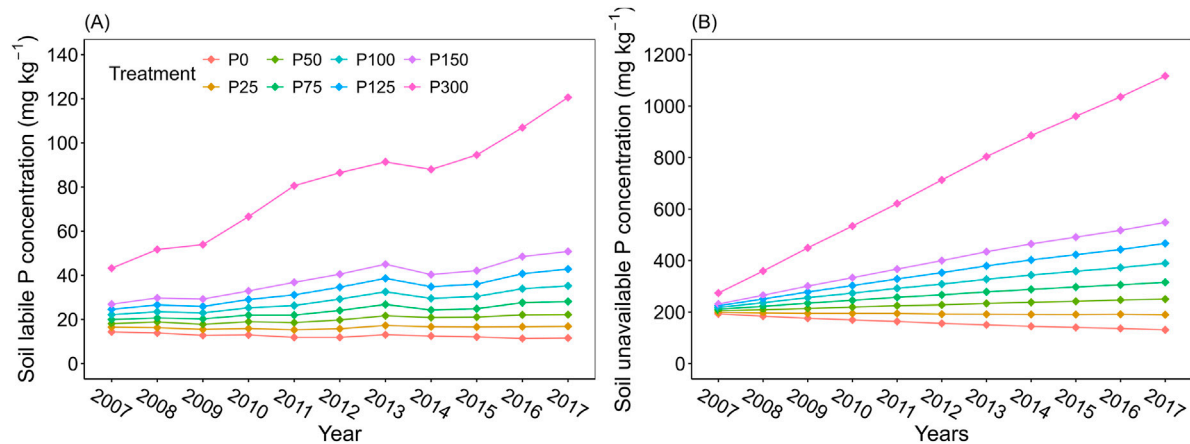


FIGURE 5 | Dynamic changes in soil available P concentration (A) and steady-state P concentration (B) under different P application treatments simulated by the revised APSIM v7.9 model from 2007 to 2017.

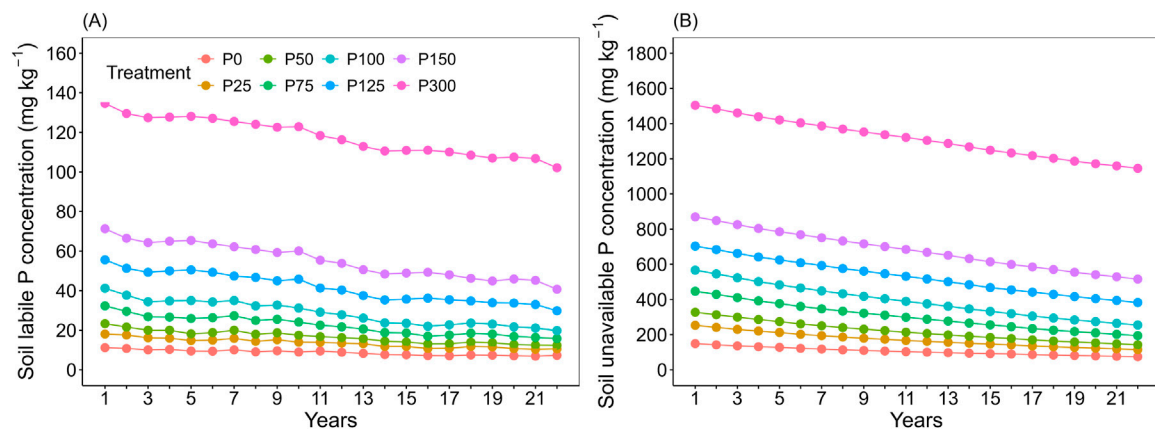


FIGURE 6 | Dynamic changes in soil available P concentration (A) and steady-state P concentration (B) after 22 years of no fertilization under different soil baseline P concentration conditions, simulated by the revised APSIM v7.9 model.

(Zhang et al., 2018). Comprehensive calibration of these parameters, including thermal time requirements, light interception algorithms, RUE adjustments, and P allocation thresholds of this research program was shown in **Table 1**, ensuring model fidelity to regional agroecological conditions.

Predicting the Soil P Pools Dynamics and Optimal P Fertilization Rate Based on Scenarios Analysis

The calibrated APSIM model was employed to evaluate long-term P fertilization management effects on maize growth and soil P pool dynamics in Quzhou County. Scenario analyses of field P management practices focused on crop-soil system responses under varying P application rates. Eight P fertilization rate levels (0–300 kg P₂O₅ ha⁻¹) were simulated: 0 (P0), 25 (P25), 50 (P50), 75 (P75), 100 (P100), 125 (P125), 150 (P150), and 300 (P300) kg P₂O₅

ha⁻¹. Single superphosphate (SSP) was selected as the P source, with full-dose basal application at a 5 cm soil depth. To eliminate water stress effects, automated irrigation was triggered when soil moisture dropped below 85% of field capacity. Model outputs encompassed interannual variations in crop biomass, grain yield, P uptake, and soil P pools (labile P and unavailable P fractions). This configuration enables systematic quantification of legacy P effects, fertilizer utilization efficiency, and environmental risks under continuous P fertilization regimes.

RESULTS

Response of Maize Growth to Long-Term P Application (2007–2017)

The influence of soil P supply intensity on aboveground biomass and yield of maize exhibited significant interannual variations

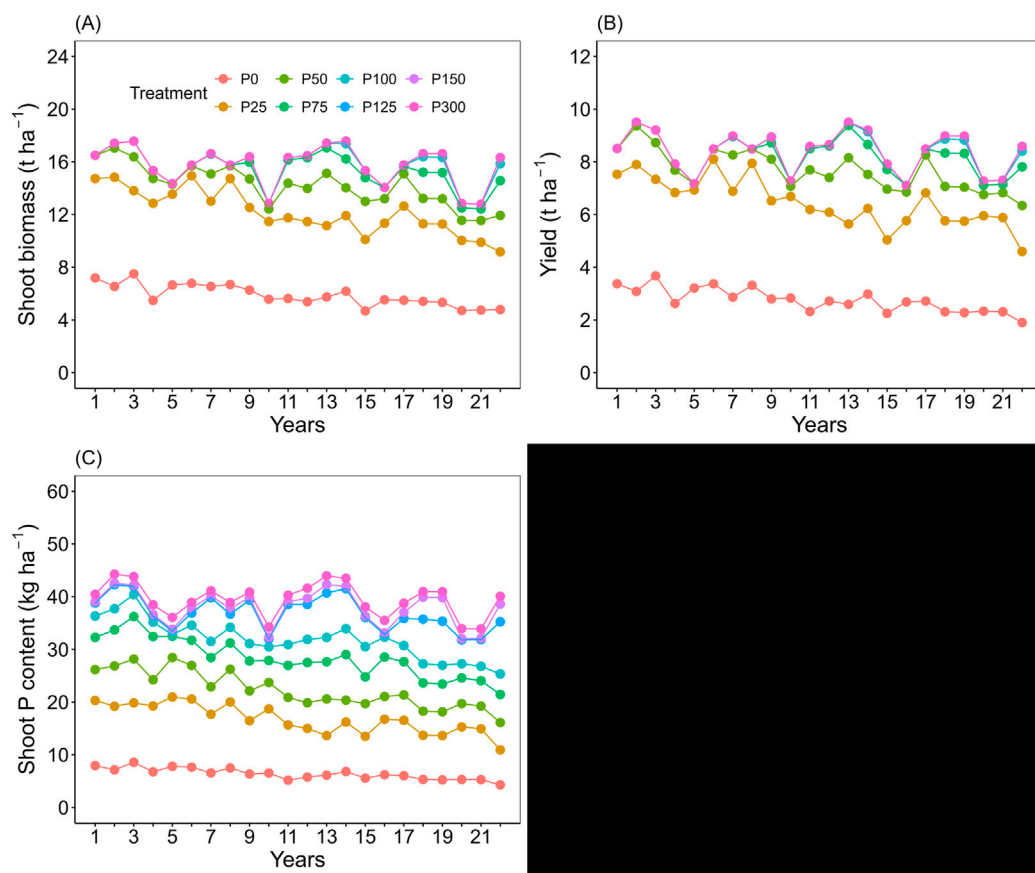


FIGURE 7 | Dynamic changes in maize aboveground biomass (A), yield (B), and aboveground P content (C) after 22 years of no fertilization under different soil baseline P concentration conditions, simulated by the revised APSIM v7.9 model.

(Figure 2). From 2007 to 2017, maize yield demonstrated a gradual increasing trend with elevated P supply intensity. However, during 2007–2009, no significant differences in maize biomass or yield were observed among P fertilizer treatments, indicating that soil P supply intensity did not substantially affect maize growth during the initial 3 years of the experiment. From 2010 to 2013, both biomass and yield under the P75 treatment were significantly higher than those under the P0 treatment. Notably, maize yield in 2014 under equivalent P fertilizer treatments significantly higher than that of other years with. Thus, the P75, P100, P125, P150, and P300 treatments resulted in significantly greater maize biomass and yield compared to P0, and P0 showed significant decrease both in shoot biomass and yield when compared to P25 and P50 treatments (Figure 2).

Aboveground biomass, grain yield, and P uptake in maize shoots increased significantly with increased P application rates (Figure 3). The linear-plateau model was used to describe the relationship between P application rates and maize shoot biomass ($R^2 = 0.607$), yield ($R^2 = 0.627$) and shoot P uptake ($R^2 = 0.860$) (Figure 3). The critical P fertilization rate was different among maize shoot biomass, yield and shoot P uptake. For shoot biomass and yield, the critical P fertilization rate was ranged from 64.5 to

71.0 kg ha^{-1} . In contrast, the critical P application rate for shoot P uptake was 193.5 kg ha^{-1} .

The incremental gains in maize biomass and yield across P application treatments exhibited diminishing trends with increasing P inputs (Figures 4A,B), accompanied by a gradually decline in P use efficiency (PUE) (Figure 4C). When P fertilizer application exceeded 75 $\text{kg P}_2\text{O}_5/\text{ha}$, the biomass and yield increments per kilogram of applied P_2O_5 significantly decreased from 92 $\text{kg/kg P}_2\text{O}_5$ and 52 $\text{kg/kg P}_2\text{O}_5$ to 25 $\text{kg/kg P}_2\text{O}_5$ and 15 $\text{kg/kg P}_2\text{O}_5$ at P300, respectively (Figures 4A,B). Meanwhile, PUE declined from 17% at 75 $\text{kg P}_2\text{O}_5/\text{ha}$ to 10% under the 300 $\text{kg P}_2\text{O}_5/\text{ha}$ treatment (Figure 4C).

Dynamics of Soil P Accumulation Under Continuous P Fertilization (2007–2017)

Under long-term P fertilization, both soil available P (labile_P) and steady-state P concentrations (unavail_P) exhibit progressive accumulation. Figure 5 illustrates the divergent temporal trajectories of labile_P and unavail_P concentrations in calcareous soils under long-term P fertilization regimes during 2007–2017. Over this 11-year period, all P-fertilized treatments except P0 and P25 demonstrated significant increases in soil

available P concentrations: P50 (18.1 → 22.2 mg/kg), P75 (20.0 → 28.1 mg/kg), P100 (22.2 → 35.2 mg/kg), P125 (24.6 → 42.8 mg/kg), P150 (26.9 → 50.8 mg/kg), and P300 (43.2 → 121 mg/kg). Conversely, P0 treatment showed a decline in topsoil available P concentration from 14.4 to 11.6 mg/kg. A parallel accumulation pattern was observed for unavailable P concentrations across all fertilized treatments except P0 and P25: P50 (205 → 250 mg/kg), P75 (212 → 316 mg/kg), P100 (218 → 389 mg/kg), P125 (225 → 467 mg/kg), P150 (231 → 549 mg/kg), and P300 (274 → 1,117 mg/kg). The P0 treatment exhibited a marked reduction in topsoil steady-state P concentration from 193 to 131 mg/kg. Notably, Bai et al. (2013) established environmental thresholds for soil available P concentrations across Chinese agricultural soils, ranging from 39.9 mg/kg (Yangling Lou soil) to 90.2 mg/kg (Qiyang Red soil). Given the calcareous soil characteristics of Quzhou, the regional environmental threshold for available P should not exceed 39.9 mg/kg. While the P75 treatment maintained available P concentrations below this critical threshold (32.0 mg/kg in 2017), persistent P accumulation poses ongoing environmental risks. Of particular concern is the P100 treatment, where available P concentrations surpassed the threshold (40.8 mg/kg in 2017). The 23% steady-state P increase observed between P75 and P100 treatments demonstrates a substantial reservoir for available P replenishment, significantly elevating the probability of threshold exceedance. This phenomenon highlights the critical need for optimized P management strategies to mitigate environmental risks while maintaining agricultural productivity in calcareous soil systems.

Long-Term Transformation of Soil P Pools Following 22-Year Cessation of P Fertilization

Figure 6 illustrates the dynamic changes in soil available P and steady-state P pools across various P-fertilization treatments following prolonged application (2007–2017) and a subsequent 22-year cessation period. During the 22-year post-application phase, all P-treated soils exhibited continuous declines in available P concentrations: P0 (11.2 → 7.3 mg/kg), P25 (18.1 → 10.6 mg/kg), P50 (23.3 → 12.4 mg/kg), P75 (32.3 → 15.8 mg/kg), P100 (41.2 → 19.8 mg/kg), P125 (55.6 → 29.8 mg/kg), P150 (71.3 → 40.7 mg/kg), and P300 (134.6 → 102.1 mg/kg). A parallel decreasing trend was observed for unavailable P concentrations across all treatments: P0 (149 → 74.7 mg/kg), P25 (253 → 115 mg/kg), P50 (327 → 142 mg/kg), P75 (447 → 195 mg/kg), P100 (567 → 254 mg/kg), P125 (703 → 383 mg/kg), P150 (869 → 516 mg/kg), and P300 (1,504 → 1,145 mg/kg). These systematic reductions in both available P and steady-state P pools highlight the gradual depletion of legacy P reserves in calcareous soils under extended fertilization discontinuation, emphasizing the critical hysteresis effect between historical P inputs and long-term soil P dynamics. The differential residual P persistence across treatment gradients (e.g., P300 maintaining SSP >1,000 mg/kg post-cessation) underscores the nonlinear relationship between initial P loading intensity and environmental legacy duration.

Figure 7 illustrates the dynamic changes in maize aboveground biomass, grain yield, and P uptake under different long-term P fertilization regimes following P withdrawal. After 22 years of continuous P deprivation, both biomass production and grain yield in P0, P25, and P50 treatments exhibited progressive decline (**Figure 7A**). In contrast, the P75 maintained biomass and yield levels comparable to those of P100, P125, P150, and P300 treatments, demonstrating sustained high productivity (**Figures 6A,B**). Notably, long-term fertilization (75 kg P₂O₅ ha⁻¹ yr⁻¹ for 11 years) builds up significant legacy P reserves, sustaining maize yields at 8–10 t ha⁻¹ for 12–13 years after stopping P applications without yield decline (**Figure 7B**). Shoot P content increase along with the increase of P fertilization rate, and treatments P0–P100 displayed continuous diminishing trends, while P125–P300 treatments maintained elevated P uptake capacities without observable downward trajectories over the experimental duration (**Figure 7C**). In the maize shoots, P content exhibited a consistent decreasing trend with treatments P0, P25, P50, P75, and P100. In contrast, treatments P125, P150, and P300 maintained elevated P uptake (approximately 40 kg ha⁻¹) without showing a significant downward trend (**Figure 7C**).

DISCUSSION

Effects of Different Long-Term P Fertilization on Maize Yield, Biomass Accumulation, and P Uptake Dynamics

Figure 2 demonstrates that maize biomass and grain yield exhibited no significant declines during the initial three experimental years (2007–2010) under zero or low P supply regimes, indicating that initial soil P concentration sufficiently met crop demands during this period. This observation aligns with Jiao's (2016) findings that residual soil P can sustain maize productivity for three consecutive years without P fertilization. The residual P pool in agricultural soils has been recognized as a critical potential P resource for sustainable crop production (Sattari et al., 2012). Empirical evidence from multiple long-term studies consistently confirms that legacy P in cultivated soils can effectively satisfy crop P requirements under optimized management conditions (Aulakh et al., 2007; Valkama et al., 2009, 2011). Based on the integrated assessment of aboveground biomass, grain yield, and P uptake, the optimal P fertilizer application rate was determined to be 71 kg P₂O₅/ha (**Figure 3**). At 71 kg P₂O₅ ha⁻¹ application rate, both maize biomass and grain yield were maintained at highest level with 17.5 t ha⁻¹ and 9.28 t ha⁻¹, respectively. Maize P uptake was only 23 kg ha⁻¹ (**Figure 3C**). Therefore, 71 kg P₂O₅ ha⁻¹ application rate can help to achieve the dual objectives of ensuring food security and conserving P rock resources.

Following 25 years of continuous P fertilization, both peanut and rapeseed systems demonstrated the capacity to sustain yields for three subsequent years without P application by utilizing residual soil P pools (Aulakh et al., 2007). In high P-fixing soils

such as red soils, a single high-dose P application enabled crop production to remain stable for 7–9 years under subsequent P withdrawal regimes (Kamprath, 1967). This phenomenon extends beyond field-scale observations to regional patterns: Japan achieved maintained crop yields from 1985 to 2005 despite progressive reductions in both mineral and organic P fertilizer inputs (Sae and Kohyama, 2010). Similarly, European Union nations observed stabilized or even enhanced agricultural productivity post-1980s alongside declining total P fertilizer usage, attributable to efficient legacy P mobilization (Sattari et al., 2012). These findings collectively demonstrate crops' ability to exploit residual soil P reserves to buffer yield declines during P fertilizer application reduction.

Long-Term P Supply Intensities Modulate Soil P Pool Dynamics: Implications for Fertilization Management Strategies

The APSIM model has incorporated a soil P module (soilP module) and coupled it with crop modules to simulate crop growth responses to soil P availability (Delve et al., 2009; Wang et al., 2014). This study represents the first application of this framework to simulate maize growth responses to P fertilization in fluvo-aquic soils of the North China Plain. Soil organic and inorganic P pools exhibit fundamentally distinct transformation pathways (Hansen et al., 2004; Turner and Leytem, 2004), accounting for 30%–65% and 35%–70% of total soil P respectively (Condrón et al., 2005; Shen et al., 2011). The organic P pool predominantly exists in stabilized forms and contributes to available P through mineralization processes (Shen et al., 2011), with mineralization rates being regulated by soil moisture, temperature, and chemical properties. Inorganic P speciation varies significantly between soil types. In acidic soils, P primarily associates with Fe/Al oxides or forms complexes with clay minerals through adsorption processes, while desorption mechanisms can release P into soil solution. Conversely, in neutral/calcareous soils, phosphate ions tend to precipitate on calcium carbonate surfaces. The dissolution of these P precipitates becomes enhanced under decreasing soil pH conditions, thereby increasing labile P availability (Wang and Nancollas, 2008). These transformation pathways—encompassing adsorption-desorption equilibria, precipitation-dissolution reactions, and mineralization processes—constitute a complex dynamic system that requires comprehensive evaluation to advance our understanding of P cycling in agricultural ecosystems.

In the soil P module of the APSIM model, two principal P transformation processes are incorporated: 1) the mineralization/immobilization process between organic P pools and labile P pools, and 2) the sorption/desorption process between stable inorganic P pools and labile P pools (Delve et al., 2009; Wang et al., 2014). These core processes enable the model to accurately simulate P stress conditions in soils of eastern Kenya and the effects of P fertilizer types (chemical or organic) on maize biomass accumulation and grain yield (Kinyangi et al., 2004; Micheni et al., 2004; Probert, 2004). The module has also demonstrated robust performance in simulating crop rotation

systems in Australia (Wang et al., 2014) and P dynamics across diverse soil types for maize and soybean cultivation (Delve et al., 2009). Our findings confirm the model's capability to realistically simulate maize biomass growth and P uptake patterns (Zhang et al., 2024). However, it should be noted that the current APSIM P module calculates labile P content primarily through sorption/desorption mechanisms while neglecting the predominant precipitation/dissolution processes that govern P availability in neutral/calcareous soils. This limitation may constrain the model's accuracy in simulating labile P dynamics in soils where precipitation-dissolution equilibria prevail. To enhance the model's performance and broaden its applicability across pedologically diverse systems, further experimental data quantifying P fractionation and transformation kinetics across different soil types are critically required. We employed the APSIM model in conjunction with a scenario analysis approach to systematically evaluate maize productivity, P utilization efficiency (PUE), and the dynamics of soil P pools across different long-term P fertilizer application strategies. This integrated methodology establishes a robust quantitative framework to inform future long-term experimental research.

CONCLUSION

Our study used the parameter-calibrated APSIM model to conduct scenario analyses of maize growth under varying P application levels in the North China Plain. Simulation results demonstrate that 71 kg P₂O₅/ha constitutes the optimal P application rate for maize production in this region. Beyond this threshold, the marginal productivity of P fertilizer declines substantially, with incremental biomass and grain yield per kilogram of applied P₂O₅ significantly decreased. Concurrently, PUE diminishes from 17% at 75 kg P₂O₅/ha to 10% at 300 kg P₂O₅/ha. However, under sustained P75 fertilization regimes, continuous accumulation of labile and stable inorganic P pools in soil is observed. Long-term field simulations reveal that maize yields can be maintained at 8–10 t/ha for 12–13 years following P75 application without additional P inputs. Considering the maize productivity and environmental implications of soil P accumulation suggests that following a decade of annual 75 kg P₂O₅ ha⁻¹ applications, P fertilization discontinuation for 12–13 years enables effective mobilization of legacy P pools while maintaining grain yields at 8–10 t ha⁻¹, demonstrating sustainable P management through residual nutrient utilization. This approach enables efficient utilization of residual soil P while sustaining high yield levels (8–10 t/ha), thereby achieving dual objectives of P resource conservation and pollution mitigation without compromising crop productivity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

WZ performed the experiments and analyzed the data. DX, HW, BJ, CL, MH, ZC, XZ conceived the idea. DS, MY, and JL critically revised the article. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The 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.

GENERATIVE AI STATEMENT

The author(s) declare that Generative AI was used in the creation of this manuscript. We used AI polished the language.

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