Potential use of phosphorus saturation degree as combined indicator for crop yield and leaching risks at regional scale

European Journal of Agronomy

Gu, Yu; Ros, Gerard H.; Zhu, Qichao; van Doorn, Maarten; Shen, Jianbo et al

https://doi.org/10.1016/j.eja.2024.127347

European Journal of Agronomy 161 (2024) 127347

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Potential use of phosphorus saturation degree as combined indicator for crop yield and leaching risks at regional scale

Yu Gu [a,b,c], Gerard H. Ros [a], Qichao Zhu [b,c], Maarten van Doorn [a,d], Jianbo Shen [b,c,*], Zejiang Cai [e,f], Minggang Xu [e,f], Wim de Vries [a]

[a] Wageningen University and Research, Earth Systems and Global Change Group, PO Box 47, Wageningen 6700AA, Netherlands
[b] National Academy of Agriculture Green Development, China Agricultural University, Beijing 100193, China
[c] State Key Laboratory of Nutrient Use and Management, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[d] Nutrient Management Institute, Nieuwe Kanaal 7C, Wageningen 6709PA, the Netherlands
[e] National Engineering Laboratory for Improving Quality of Arable Land, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[f] Qiyang Agro-ecosystem of National Field Experimental Station, Hunan 426182, China

ARTICLE INFO

Keywords:
Phosphorus
Phosphorus saturation degree
Crop yield
Leaching risk
Long-term experiment

ABSTRACT

To ensure the sustainable use of phosphorus (P) fertilizers it is necessary to develop P management strategies that maximize crop yield while minimizing P leaching. Current P management practices, based on single agronomic soil P tests such as Olsen P (P_{OLSEN}), do not consider the P sorption capacity allowing one to predict soil P dynamics in response to long-term P inputs and related impacts on crop yield, P uptake and P loss. The oxalate extraction method, measuring contents of P, aluminium (Al) and iron (Fe), has been identified as a high-potential agri-environmental P test as it measures the reversibly sorbed P pool. This test gives insights in the plant-available P pool, the P sorption capacity and the degree of P Saturation (PSD). In this study, we evaluated the performance of P_{OLSEN} and PSD in explaining crop yield and P leaching risks, using long-term field experiments from China (n = 1) and Europe (n = 11), and we applied these insights to an inventory dataset (grid-sampling based) of Qiyang county in China. The variations in crop yield and P leaching risk were better explained by PSD (R^2=0.5–0.95 for crop yield and 0.84–0.95 for P leaching risk) than by P_{OLSEN} (R^2=0.68–0.93 for crop yield and < 0.73 for P leaching risk). The PSD target level to achieve 90 % of the potential yield was higher than the critical level to avoid enhanced P leaching for the Chinese but not for the European experiments. When applied on regional scale, we showed that the use of P_{OLSEN} might underestimate P demand for crop production and overestimate the potential leaching risk. Considering the theoretical advantages of PSD as a combined agri-environmental soil P test, we discussed the implications of its use for regional P management and showed that the α value, which is used to estimate PSD from oxalate extractable Al and Fe, needs to be adjusted for regional pedogenic and related climate factors.

1. Introduction

Sustainable Phosphorus (P) management in agriculture strives to grow crops without P limitations while preventing unacceptable P losses to the environment. Such management is urgently needed since many regions worldwide have transitioned from P deficiency to a state where crop yield is no longer limited by P. Unfortunately, excessive P application has led to serious adverse impacts on water quality and related eutrophication of aquatic ecosystems (Zou et al., 2022). Accumulated P losses from soils have been estimated to exceed the safe operating space for humanity regarding the phosphorus inputs to freshwaters and coastal oceans (Rockström et al., 2023; Springmann et al., 2018; Steffen et al., 2015). The concern of high agricultural P inputs and low P use efficiency is particularly true in countries like Western Europe, India and China (Zou et al., 2022; McDowell et al., 2024). For example, P inputs in Chinese croplands have increased 13-fold in the last four centuries (Liu et al., 2016). Currently, China consumes 30 % of the global P fertilizer use (Smit et al., 2009), resulting in an annual mean P surplus of more than 90 kg P ha^{-1} in cropland soils (Zhang et al., 2019). Given the limited availability of phosphate rock resources (Cordell et al., 2009;

* Corresponding author at: National Academy of Agriculture Green Development, China Agricultural University, Beijing 100193, China.
E-mail address: jbshen@cau.edu.cn (J. Shen).

https://doi.org/10.1016/j.eja.2024.127347
Received 5 February 2024; Received in revised form 5 September 2024; Accepted 5 September 2024
Available online 19 September 2024

Gilbert, 2009) and the increasing awareness of adverse environmental impacts of P overuse, optimizing P management is key for sustainable agronomic systems. Sustainable P use in agriculture implies therefore finding a balance between crop yield and environmental impacts induced by P losses.

In agronomy, the build-up and maintenance approach has been used to develop fertilization guidelines for maximizing crop yield while maintaining high P use efficiency and minimizing P losses in the field. This approach aims to bring all soils to an optimum P status required for achieving target crop yield. Once this optimum level is reached, only the P removal by the crop needs to be replenished by P fertilizers. Traditional agronomic soil P tests, based on the extraction of the soil with various extractants, are frequently used to define this optimum level by calibrating the crop yield response to P inputs over soils varying in soil test P levels (SPT) (Tandy et al., 2021). The different soil tests can be categorized as P intensity and P quantity measures. The P intensity measures are defined as proxies for the P concentration in soil solution, while the P quantity measure the amount of P that will replenish the soil solution and be taken up by the crop during the season (Van Rotterdam et al., 2012). The buffer power is defined as the ability of the soil to maintain the P intensity upon addition or removal of P, thereby combining the soils P intensity and P quantity as it is directly related to the slope of this isotherm (Barrow, 1967). Target values for P_{OLSEN} (extracted by sodium bicarbonate solution) to avoid yield losses have been identified to range from 10 to 28 mg kg^{-1}, depending on soil properties and crop species (Bai et al., 2013). Similarly, critical SPT values have been established for soil tests using ammonium oxalate, ammonium lactate, calcium chloride and water as extraction method (Nawara et al., 2017; Siatwiinda et al., 2024). All the current SPTs may be an indicator of either P intensity or P quantity, but they cannot be used as indicator of the buffer power, leading to significant variations in the target SPT values for the optimum soil P status (Amery et al., 2021).

Various soil properties, such as amorphous and crystalline iron and aluminium oxides, pH and soil organic matter (SOM), govern desorption and adsorption processes as well as the P sorption capacity (Møller et al., 2023) thereby determining the buffer power. This, in turn, regulates the availability of P for crop growth and potential risk of P leaching (Amery et al., 2021; Fischer et al., 2017; Lookman et al., 1996). Furthermore, soil properties also affect the changes in soil P status resulting from P inputs, thereby impacting P dynamics and long-term P availability in response to P fertilization. Given the need to optimize fertilization schemes to balance crop yield and environmental risks, there is an urgent need for a more mechanistic underpinned SPT that can link soil P status and soil P supply to crop demand and potential leaching risks.

The soil P saturation degree (PSD), which is generally defined as “the fraction of surface coverage with phosphate” (Beauchemin and Simard, 1999), being determined via ammonium oxalate extractable P (P_{OX}) divided by the phosphate sorption capacity (PSC), is the most common SPT to assess the potential of P losses from soil to water. The PSD is based on the 0.2 M acid ammonium oxalate extraction method of Schwertmann (1964a). Amorphous Fe- and Al-(hydr)oxides and P reversibly bound to those oxides are simultaneously extracted from soil. Subsequently, the PSC is derived as the sum of Fe- and Al-(hydr)oxides (estimated by ammonium oxalate extractable iron and aluminium, i.e. Fe_{OX} and Al_{OX}) multiplied with an empirical maximal saturation factor (the α value). The PSD therefore incorporates both a measure of the PSC, which affects the potential leaching risks, and the total pool of reversibly bound P (P_{OX}) acting as a reserve for plant-available P (Schoumans and Chardon, 2015).

Unlike existing agronomic SPTs correlating P pools in soil to crop P response, such as P_{CACL2} and P_{OLSEN}, PSD serves as a soil P indicator, that accounts for the P buffer capacity, thus allowing one to predict the changes in soil P availability and the potential leaching risk in response to P inputs. Most P sorption in non-calcareous soils occurs at the surfaces of amorphous iron and aluminium oxides (Møller et al., 2023) implying that the P in soil solution is controlled by both a sorption maximum as well the sorption affinity, often described via Langmuir sorption isotherm. The PSD has been introduced as a soil P indicator in the 1990s (Van der Zee et al., 1987) given its potential to assess P leaching losses from agricultural systems. High PSD soils, where most of the soil's adsorbed sites have been occupied by phosphate, are vulnerable to P losses, making PSD relevant for assessing P management implications on water quality (Fischer et al., 2017; Nair et al., 2004). Additionally, PSD allows for estimating the changes in P availability as a function of P inputs, as changes in P_{OX} linearly reflects the changes in P accumulation over time (Gu et al., 2023), showing less dependancy on soil properties and smaller temporal variation compared to P_{OLSEN} or P_{CACL2} (Zheng, 2024). Therefore, the PSD can be considered as a key factor regulating P in soil solution and might also be used as agronomic soil P test determining the optimum soil P status for crop yields thereby guiding the fertilizer application. However, limited studies have evaluated the performance of PSD in predicting crop responses. While critical values for other SPTs, such as P_{OLSEN}, have been derived at (long-term) experimental sites for specific crops, their use in fertilizer applications at region level is hampered since soil properties might differ from those at the experimental sites (Lemaire et al., 2021; Hirte et al., 2021). The use of PSD might avoid or minimize this dependency on soil properties.

Given the potential advantages of the PSD for characterizing current and long-term P availability and environmental risk (Van Doorn et al., 2024), this study aims to evaluate its performance to assess the crop response and potential P leaching risks simultaneously. The performance is compared to that of P_{OLSEN} being the SPT currently used in China. To compare the performance, we (a) evaluated the relationship between PSD and P_{OLSEN} with both the relative crop yield and the concentration of P_{CACL2} (extracted by calcium chloride solution), using long-term experimental observations in subtropical China (n = 1) and Europe (n = 11); (b) assessed the difference in the spatial variation in risks for crop P limitation and enhanced P losses at the regional level in Qiyang county when using PSD or to P_{OLSEN}. Finally, we discuss the applicability of PSD for regional P management.

2. Materials and methods

A long-term field experiment and regional soil datasets from China were used to evaluate the potential of PSD for agronomic applications at the field and regional level. In addition, published results from 11 long-term field studies in Europe were further evaluated to underpin the results.

2.1. Field experiment in China

A long-term field experiment was set up in 1990 at the Qiyang Experimental Station experiment station (26°45'12'', 111°52'32'') of the Chinese Academy of Agricultural Sciences, Qiyang, Hunan Province, China. The field is located on a non-calcareous upland red soil, Ferralic Cambisol, in the FAO classification system (Cai et al., 2014). The cropping system is a continuous rotation of winter wheat and summer maize. The field experiment was designed as a randomized complete block design with three replicates. For this study, six fertilization treatments were chosen with various combinations of fertilizer nitrogen (N), P, and potassium (K) inputs in organic and/or inorganic form. More details of the agri-ecosystem properties and the treatments applied are given by Gu et al. (2023). In brief, these include an unfertilized control (CK), applications of N-P-K fertilizers (NPK), and combinations of N-P-K fertilizers with typical doses of manure (NPKM) or high amounts of manure (HNPKM). The total P input ranged from 52 to 320 kg P ha^{-1} yr^{-1}, with inorganic P inputs ranging from 52 to 79 kg P ha^{-1} yr^{-1}. Inorganic N and K fertilizers were applied at a dose of 90 – 300 kg N ha^{-1} and 100 kg K ha^{-1} per year. Although K and N input fluctuated in different treatments, impacts on P dynamics were small (Gu et al., 2023).

In total, 17 soil samples were collected annually from the plough layer (0–20 cm), and various P pools were determined, including of

P_{CACL2}, P_{OLSEN}, P_{OX} and P_{TOTAL}. Both P_{OLSEN} and P_{TOTAL} were determined in the year of sampling for each soil sample. P_{OLSEN} was determined through soil extraction with 0.5 M $NaHCO_3$ adjusting pH to 8.5 (2.5 g soil, 50 mL solution, 25 °C, shaken for 30 minutes) followed by colorimetric measurement (Thermo Fisher 3020, Finland) of P by molybdate-ascorbic acid method (Murphy and Riley, 1962). Next, P_{TOTAL} was analyzed using the colorimetric and molybdate-ascorbic acid method (Murphy and Riley, 1962) after oxidative digestion of the samples with a mixture of concentrated H_2SO_4 and HNO_3 (Bao, 2000). The P pools extracted with 0.01 M $CaCl_2$ (being a proxy for the P pool in soil solution) and ammonium oxalate (being a reactive P pool) and the amount of Fe_{OX} and Al_{OX} were measured in 2020 for all the historical samples collected. The P_{CACL2} content was determined by 0.01 M $CaCl_2$ extraction (soil: solution is 1:5, 25 °C), shaken for 15 mins, followed colorimetric analysis as described for P_{TOTAL}. Finally, P_{OX}, Al_{OX} and Fe_{OX} were extracted by 0.175 M oxalate-ammonium oxalate buffer (McKeague and Day, 1966) and further determined by Inductive Coupled Plasma Emission Spectrometer (ICP-OES) (radial ICAP 6300 series, Thermo Scientific). The acid-oxalate extraction was done following McKeague and Day (1966) thereby ignoring the potential impact of carbonates on the release of Fe, Al and P in calcareous soils since most of the soils are non-calcareous (Xu et al., 2022).Data on annual crop production, maize and wheat (including straw) were collected from a historical database. Crop products and residues were manually harvested, dried, weighed, and grinded for total P analysis (Bao, 2000). After digestion by concentrated nitric acid, the P concentration was measured by molybdate-ascorbic acid (Bao, 2000).

2.2. Field Experiments in Europe

To get more insight into the performance of PSD in predicting both crop response and potential leaching risk, we evaluated the value of PSD for application in China using critical values derived from European experiments as published by Nawara et al. (2017). A total of 218 soil samples were collected between 1980 and 2015 for 11 long-term experiments in five European counties (Table S1). The detailed study site, soil types, fertilizer history, and crop rotation are described by Nawara et al. (2017). Other nutrients (e.g., N and K) had been applied in sufficient amounts. Only data from wheat and maize crops were selected. Soil samples were collected and analysed for P_{CACL2}, P_{OLSEN}, P_{OX}, Fe_{OX} and Al_{OX} based on the same methods being applied in the field experiment in China, with slightly differences in extraction conditions for P_{CACL2} and P_{OX}, which impacts will be discussed later.

2.3. Regional sampling dataset in Qiyang county

In 2014, a grid-based soil sampling campaign (2.7 km • 2.7 km) was carried out across Qiyang (Zhou, 2017). Qiyang county (26°02′N-26°51′N, 110°35′E-112°14′E) locates in Hubei province, the central south of China. The climate in the county is mild and humid subtropical. The soils, including calcareous and non-calcareous soils, in Qiyang county are covered for 45 % with agricultural crops, including upland crops (24 %) and rice (21 %), while the remaining other land use types (55 %) mainly include forest and municipal land (Figure S1). The mean annual temperature is 18 °C and the annual rainfall is 1325 mm (Cai et al., 2015). A total of 123 soil samples in cropland were collected from the topsoil of 0–20 cm in each grid (Xu et al., 2022). The concentrations of P_{CACL2}, P_{OLSEN}, P_{OX}, P_{TOTAL}, Fe_{OX} and Al_{OX} in each soil sample were determined via the methods described in Section 2.1.

2.4. Data analysis

2.4.1. Calculation of the phosphorus saturation degree

The P saturation degree (PSD) was calculated as:

$$PSD = \frac{P_{OX}}{\alpha * \quad [Fe_{OX} + Al_{OX}]} \tag{1}$$

where P_{OX}, Fe_{OX} and Al_{OX} are oxalate extractable contents of P, Al and Fe (mmol kg^{-1}), and the scaling factor α represents the fraction of available oxides (Fe_{OX} and Al_{OX}) contributing to P sorption (Sharpley et al., 2020). The value of α varies mostly between 0.3 and 0.7 with a value of 0.5 being most commonly used for non-calcareous sandy soils (Van der Zee et al., 1987; Lookman et al., 1996; Schoumans and Chardon, 2015). However, it can vary much more when weathering rates greatly differ due to variation in pedogenesis history induced by climate, vegetation and geographical position. For example, in Brazil soils with a range of chemical, physical and mineralogical features, α values varied from 0.29 to values even exceeding 1.0 when using sorption experiments to determine the fraction of the potential retention capacity that can be occupied by P (De Campos et al., 2018) implying that under certain conditions other processes than sorption to metal(hydr)oxides might play a role in retaining P. In the long-term experiments in China and Europe, the majority of the soils were non-calcareous with a sandy to loamy texture and hence α was first assumed to be 0.5, implying that halve of the total aluminium and iron oxides contribute to the PSC. To account for the influence of pedogenesis factors in the subtropical climate, the α value was adjusted for the Qiyang experiment to 0.8 based on incubation trials from tropical soils published in literature (Table S2) in order to avoid extreme high optimum P levels for both P_{OLSEN} and PSD (Wu et al., 2020).

2.4.2. Calculation of P thresholds in view of crop production and leaching risk

To minimize the effect of crop types and sites conditions (e.g., climate, soil types) on the relationship between soil P pools and crop yield in the European and Chinese long-term experiment, the relative yield (Y_R) was calculated (Zhu et al., 2020) as:

$$Y_R = \frac{Y_T}{Y_M} \tag{2}$$

where Y_T is the treatment yield (kg ha^{-1}) and Y_M is the maximum yield (kg ha^{-1}) among all treatment means per year, being the treatment with the highest P fertilization in the majority of the years.

An asymptotic regression model was subsequently applied to examine the relationship between relative crop yields and soil P test (SPT) values for the Qiyang experiment in China, for four European experiments (having sufficient observations (Table 3) and for all European experiments together via:

$$Y_R = Y_{RM} + B \bullet \exp(-C \bullet SPT) \tag{3}$$

where Y_{RM} represents the maximum relative yield (%), and B and C are regression coefficients describing the response of the crop yield to the P availability in soil as being measured via the soil P tests, i.e. P_{OLSEN} (mg kg^{-1}) or PSD (unitless fraction). The calibrated model coefficients and the explained variance for each SPT were evaluated to unravel the crop response to changes in soil P levels. A SPT value is considered more generic applicable when the coefficient of variation across multiple sites and crops is relatively small. We skipped observations where the pH was lower than five being observations with extremely low crop yield levels due to acidification. We excluded P_{CACL2} from this analysis since it only reflects the direct availability of P, being controlled by P inputs and the P buffer capacity, and it cannot be used as a proxy for the P buffer power, being the ability of the soil to maintain the P concentration in soil solution upon addition or removal of P. All statistical analyses were performed in R (version 4.2.2).

To determine the sensitivity of soils to P leaching, we used the P_{CACL2} concentration as a proxy of the P concentration in soil solution. Higher concentrations of P_{CACL2} will evidently lead to higher P leaching losses in situations with a precipitation surplus (Bai et al., 2013). Considering that adsorption decreases at higher adsorbed P concentration, P_{CACL2} is expected to increase exponentially with the size of reactive P pools like P_{OLSEN} or with the PSD (Bai et al., 2013; Schoumans and Chardon, 2015). In this study, we evaluated the non-linear relationship between P_{CACL2} on the one hand, and PSD and P_{OLSEN} on the other using a split-line model, to derive environmental thresholds where the P_{CACL2} starts to deviate from a linear response to a change in PSD or P_{OLSEN} (change points, also referred to as critical levels):

$$P_{CACL2} = D + E \bullet STP \text{ when } SPT < SPT_{threshold} \tag{4a}$$

$$P_{CACL2} = D + E \bullet (E - F) \bullet SPT + F \bullet SPT \text{ when } SPT > SPT_{threshold} \tag{4b}$$

where $SPT_{threshold}$ is the threshold value for the soil P test regarding the potential leaching risk and SPT represents the selected soil P test used (P_{OLSEN} or PSD); E and F are the slopes of the lines below and above $SPT_{threshold}$, respectively; and D is the intercept of the lines below $SPT_{threshold}$.

2.4.3. Upscaling of the risk of limiting crop yields and enhanced P leaching

To evaluate the potential of P_{OLSEN} and PSD in defining the occurrence of P deficiencies for crop uptake or enhanced P leaching risks for Qiyang county, the regional sampling data for both soil P indicators were interpolated at a 1 km x 1 km resolution using inverse distance weighting while accounting for differences in land use (including upland soils, paddy soils, and other land use types). The measured P_{OLSEN} and PSD values were used to classify the soil nutrient supply determining the crop response to P fertilization, according to the classic build-up-and-maintenance approach. This approach uses the categories such as “low”, “sufficient” and “high” where soils in the low status receive more P than the crop P uptake (enhancing the soil P levels) and soils in the high status receive less P than the crop P uptake (mining the soil P levels). For this study we only distinguished three classes, including “low” “medium” and “sufficient” given the present variation in P_{OLSEN}. Class F_{LOW} encompasses all situations where low P availability would lead to crop yields smaller than 80 % of the maximum crop yield. Class F_{MEDIUM} represents situations where crop yields vary between 80 % and 90 % of the maximum yield. Class $F_{SUFFICIENT}$ represents all cases with relative crop yields exceeds 90 % of the maximum crop yield, considered the threshold where P is not limiting crop yield. Similarly, we classified the soils given their potential for P leaching into three classes using the environmental critical levels from long-term experiments in China and Europe for both P_{OLSEN} and PSD, resulting in the classes E_{LOW}, E_{MEDIUM} and E_{HIGH} representing soils with a low, moderate and high potential leaching risk, respectively. These environmental class boundaries were based on the critical levels derived from the long-term experiments where E_{LOW} includes all cases where SPT was lower than 0.5 *$SPT_{threshold}$, E_{HIGH} all the cases where SPT exceeds $SPT_{threshold}$, and the E_{MEDIUM} all cases in between.

3. Results

3.1. Relationships between phosphorus indicators, crop yield and phosphorous leaching risk

The averaged P_{OLSEN} was almost five times higher in Qiyang experiment (112 mg kg^{-1}) than in the European long-term experiments (26 mg kg^{-1}), and showed a higher variation among the fertilization treatments applied (Table 1). Concentrations for P_{OLSEN} in the Qiyang experiment ranged from 3.8 to 249 mg kg^{-1} while P_{OLSEN} for Europe experiments ranged from 3.3 to 99 mg kg^{-1}. In contrast, P_{CACL2} showed the opposite pattern, with a broad range in European experiments (2.6 mg kg^{-1} on average) and a small range in the Qiyang experiment (2.3 mg kg^{-1} on average). P_{OLSEN} explained up to 93 % of the variation in relative crop yields in the Qiyang experiment, while it was 68 % in the European experiments (Fig. 1). No significant relationship was found between P_{CACL2} and P_{OLSEN} in the Qiyang experiment, while a strong relationship (R^2= 0.73, $p < 0.05$) was found in the European experiments. From the perspective of P leaching risks, a strong increase of P_{CACL2} was observed when P_{OLSEN} exceeded the 39 mg kg^{-1} in Europe experiments. However, no change point could be detected for P_{OLSEN} in Qiyang field experiment (Fig. 1).

Table 1
Overview of selected soil properties for the long-term experiments in Qiyang and Europe.

		Qiyang			Europe		
P indicator	unit	Min	Max	Mean	Min	Max	Mean
P_{OLSEN}	mg kg^{-1}	3.8	249	112	3.3	99	26
P_{CACL2}	mg kg^{-1}	0.001	5.6	2.3	0.4	19	2.6
$[Fe+Al]_{OX}$	mmol kg^{-1}	92	149	118	11	108	63
PSD (α=0.5)	/	0.02	0.78	0.22	0.02	0.43	0.13
PSD (α=0.8)	/	0.01	0.49	0.14	/	/	/

All long-term experiments in Europe and Qiyang showed strong and positive crop yields responses to the variation in PSD. The range in PSD was evidently larger in the Qiyang experiment when the α value was set at 0.5 compared to 0.8, varying from less than 5% to 78% (Table 1). The PSD explained 95 % of the variation in relative crop yields in the Qiyang experiment, but it provided a less reliable estimate for the relative crop yield in European experiments ($R^2 = 0.51$) when compared with P_{OLSEN} (Fig. 2). While the crop response gradually increased over the full PSD range in Qiyang, there was a clear change point for PSD in the European experiments, allowing to derive an evident target level for the PSD (14 %) in view of crop yield. In the Qiyang experiment, crop yield reached 90 % of the maximum when the PSD reached 31 %, with α set to 0.8 (Fig. 2). Adjusting the α value from 0.5 to 0.8 reduced the difference in critical and target levels for PSD between the Qiyang and European experiments (Fig. 2) and avoided unrealistic high SPT values found in the Qiyang experiment at an α value of 0.5 (Figs. 1 and 2). Note that the higher PSD and lower P_{CACL2} values in Qiyang can partly originate from differences in extraction methodology, but these differences likely do not affect the correlation between PSD and crop yield on the one hand, and the correlation between PSD and P_{CACL2} on the other (see Section 4.1). The variation in PSD was highly correlated with the variation in P_{CACL2}, explaining 84–95 % of its variation in both experiments (Fig. 2). The change in P_{CACL2} per unit PSD increased two to three times faster in the European than in the Qiyang experiments. Potentially high P leaching risks occurred in the European experiments when PSD exceeded 33 %, corresponding to a P_{CACL2} concentration above 2.2 mg kg^{-1} (Table 2). The change points in PSD and P_{OLSEN} occurred at similar P_{CACL2} concentrations (2.2 and 2.5 mg kg^{-1}) in the European experiments. For the Qiyang experiment, high P loss risks occurred when PSD reaches 20 % (Fig. 2).

The agronomic target levels for P_{OLSEN} and PSD were substantially higher in the Qiyang experiment than in the European experiments (Table 2). However, the difference in target levels between the two datasets was smaller for PSD than for P_{OLSEN}. The PSD target levels were three to four times higher for achieving 80 % and 90 % of the maximum yield in Qiyang (0.35 and 0.5 respectively) compared to Europe (0.11 and 0.14 respectively), while the P_{OLSEN} target levels were more than five times higher in Qiyang (44 mg kg^{-1} and 63 mg kg^{-1} for 80 % and 90 % of the maximum yield) compared to Europe (7.6 mg kg^{-1} and 10 mg kg^{-1} respectively). When tested for five experiments separately, the coefficient of variation was 1.14 for P_{OLSEN} and 0.38 for PSD (Table 3). The critical levels of PSD and P_{OLSEN} for P leaching risks in the European experiments were more than two times higher than the target levels for crop yields (Table 2). When $\alpha = 0.8$ is used in the Qiyang experiment, however, the PSD target levels for target crop yields (0.22 at

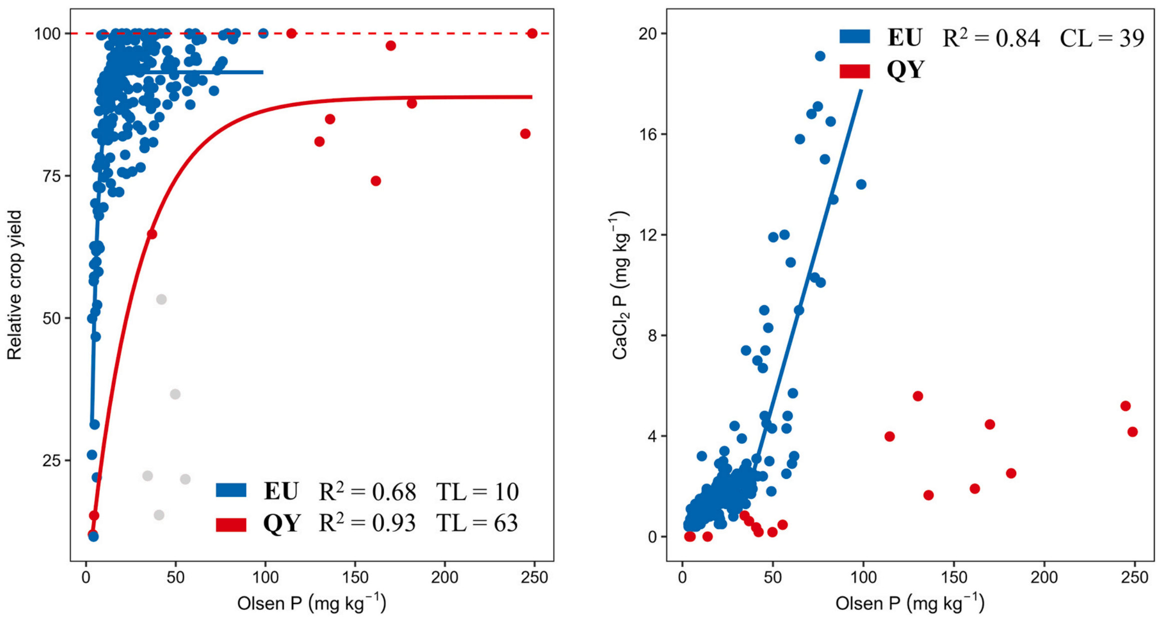

Fig. 1. Relationships between relative P_{OLSEN} and crop yield (left) and P_{CACL2} (right) for the Qiyang experiment (red QY) and European experiments (blue EU). Data points in grey were skipped from calibration because of severe crop yield reduction due to low pH values caused by acidification in response to N addition in the Qiyang experiment. TL represent target P_{OLSEN} (mg kg^{-1}) level for crop yield (90 % maximum relative yield) and CL represent critical P_{OLSEN} (mg kg^{-1}) level for potential P leaching losses.

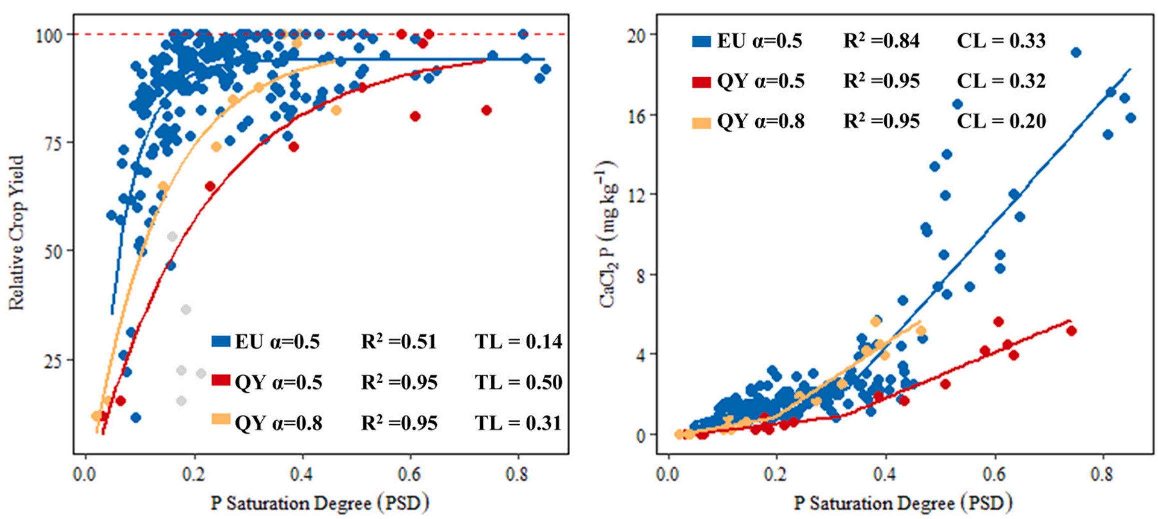

Fig. 2. Relationships between PSD and the relative crop yield (left) and P_{CACL2} (right) for both Qiyang (red for α = 0.5, yellow for α = 0.8) and European experiments (blue). Note: data points in grey were skipped from calibration (see Fig. 1). TL represent target PSD level for crop yield (90 % maximum relative yield) and CL represent critical PSD level for potential P leaching losses.

Table 2
Crop response parameters and target levels for crop yield derived for P_{OLSEN} and PSD to achieve 80 % or 90 % of the maximum yields and for critical levels for P losses derived from the Qiyang and European experiments.

		Crop response parameters			Target levels for yield		Critical levels for P losses	Corresponding P_{CACL2} [mg/kg] [a]
Site	P indicator	Y_{RM} [b]	B [c]	C [d]	80 %	90 %		
Qiyang	P_{OLSEN} (mg kg^{-1})	89	- 88	0.04	44	63	-	-
	PSD (α = 0.5)	97	−102	4.95	0.35	0.50	0.32	0.87
	PSD (α = 0.8)	**97**	**−102**	**7.39**	**0.22**	**0.31**	**0.20**	**0.87**
Europe	P_{OLSEN} (mg kg^{-1})	93	−155	0.27	7.6	10	39	2.55
	PSD (α = 0.5)	**94**	**−146**	**20.1**	**0.11**	**0.14**	**0.33**	**2.24**

[a] the corresponding P_{CACL2} for the critical levels of the P indicators P_{OLSEN} and PSD.
[b] the maximum relative yield (%)
[c] the difference in the response when input is zero and the maximum relative yield
[d] rate constant for asymptotic regression model (see Eq. 3)

Table 3
Crop response parameters and target levels for crop yield derived for P_{OLSEN} and PSD to achieve 80 % or 90 % of the maximum yields for five experiments (four in Europe and one in China, i.e. Qiyang) with the coefficient of variation in derived target levels.

	Site	Crop response parameters			Target levels for crop yield	
		Y_{RM}[a]	B[b]	C[c]	80 %	90 %
P_{OLSEN}(mg kg^{-1})	Saxmundham	96	−62	−1.3	7.4	9.8
	Rothamsted	100	−116	−1.3	8.7	11.2
	Toulouse	100	−150	−0.8	5.4	6.9
	Pierroton	99	24	−1.8	8.3	12.7
	Qiyang	89	−88	0.04	44	63
Coefficient of variation	-	-	-	-	1.11	1.14
PSD (-)	Saxmundham	98	−327	3.0	0.16	0.19
	Rothamsted	102	−432	3.3	0.12	0.15
	Toulouse	96	−368	3.1	0.14	0.17
	Pierroton	93	−0.5	3.0	0.08	0.12
	Qiyang	97	−102	7.39	0.22	0.31
Coefficient of variation	-	-	-	-	0.36	0.38

[a] the maximum relative yield (%)
[b] the difference in the response when input is zero and the maximum relative yield
[c] rate constant for asymptotic regression model (see Eq. 3)

80 % and 0.31 at 90 % of the maximum yield) were approximately two times higher than the corresponding target levels for the European experiments (0.11 and 0.14). The PSD for a target crop yield at 80 % of the maximum yield was for Qiyang close to the critical level for P leaching risk.

3.2. Spatial variation of phosphorus status in view of crop yield and leaching risks at Qiyang county

Table 4 gives the summary statistics of soil properties related to the availability of P for the 123 sampling points in Qiyang county. The soil texture is heterogenous, with a range in clay contents varying from less than 1 % up to 55 %, pH varies from 4.3 to 8.4 and SOM from 3.4 to 35 g kg^{-1}. Most sampled soils (77 from the 123) were non-calcareous (pH<7), with Fe_{OX} levels ranging from 10 to 136 mmol kg^{-1} and Al_{OX} levels from 18 to 104 mmol kg^{-1}. There was substantial variation in P_{CACL2}, P_{OLSEN} P_{OX} and P_{TOTAL} levels across the county. For example, P_{CACL2}, varied between 0.03 and 4.1 mg kg^{-1} with an average of 0.43 mg kg^{-1}. The distribution was skewed, with 70 % of the sampling points having P levels below the average. Similar skewed distributions were observed for P_{OLSEN}, with an average of 17.3 mg kg^{-1}. The relative variations in P_{CACL2}, and P_{OLSEN} across the county were comparable (Table 4). The spatial distribution in P_{OLSEN}, PSD (α=0.5), and PSD (α=0.8) is shown in Figure S2. Most of the area of Qiyang county had P_{OLSEN} values lower than 35 mg kg^{-1}, with sites with P_{OLSEN} values above 35 mg kg^{-1} mainly found in the middle-west and northern areas (Figure S2).

Table 4
Overview of soil properties of the grid sampling points in Qiyang county (123 sampling points).

Properties	Min	Max	Mean	Coefficient of variation (CV)	Median
pH	4.3	8.4	6.5	0.16	6.6
SOM (g kg^{-1})	3.4	35.3	16.4	0.43	14.8
Clay (%)	0.2	55	8	0.87	7
Fe_{OX} (mmol kg^{-1})	10	136	50	0.51	42
Al_{OX} (mmol kg^{-1})	18	104	48	0.33	44
P_{CACL2} (mg kg^{-1})	0.03	4.1	0.43	1.3	0.2
P_{OLSEN} (mg kg^{-1})	0.5	124	17.3	1.12	12
P_{OX} (mg kg^{-1})[a]	17	465	180	0.59	156
P_{TOTAL} (mg kg^{-1})	189	897	473	0.35	471
PSD[a] (α = 0.5)	0.02	0.52	0.13	0.63	0.11
PSD[a] (α = 0.8)	0.01	0.32	0.08	0.63	0.07

[a] Note that PSD is P_{OX} /(α *(Al+Fe)ox) with P_{OX} in mmol/kg, thus dividing the values in mg/kg by 31 (molar weight of P).

The variation in soil P fertility status and the hotspots for P leaching are illustrated in Fig. 3, where the target levels for relative crop yield and the critical levels for the potential leaching risk were derived from either Qiyang or European experiments. Considering that the target P_{OLSEN} level for crop yields in the experiment in Qiyang was very high (63 mg kg^{-1}) compared to literature data for China, the use of European derived target levels and critical values causes a lower area of P deficient soils and a higher area being sensitive to P leaching (Table 5). Where 97 % of the soils were classified as being P deficient when the target level for P_{OLSEN} was set at 63 mg kg^{-1}, this area declined to 7 % when the European target level was used (Fig. 3a and c). Similarly, the percentage being classified as P deficient declined from 100 down to 44 % when the soil P status was determined via the PSD (Table 5; Fig. 3b and d).

Considering the strong relationship of PSD with both crop yield and P_{CACL2} in the Qiyang experiments (Fig. 2), we also used the associated target and critical levels to analyse the regional variation in soil P status as well the leaching risks (Figs. 3b and 3f). As with P_{OLSEN}, the majority of the county was dominated by low or moderate P levels (classes F_{LOW} and F_{MEDIUM}) for crop production with less than 1 % of the area classified as soils without P deficiency risk (class $F_{SUFFICENT}$, Table 5). In contrast, using the more realistic European-derived target levels resulted in much more spatial variation in soil P fertility (Fig. 3d) where 44 % of the county was classified into the class F_{LOW} and 18 % in class $F_{SUFFICENT}$ (Table 5).

Less than 5 % of the county demonstrated a high potential risk (class E_{HIGH}) based on critical levels for both P_{OLSEN} and PSD from either Qiyang (Figs. 3e and 3f) or European experiments (Fig. 3g and h) and showed a similar spatial pattern for PSD across the county independent of the critical value set (Figs. 3f and 3h). When using an α value of 0.5 instead of 0.8 for the Qiyang-based evaluation, the moderate and high-risk areas (classes E_{MEDIUM} and E_{HIGH}) increased by 58 %, i.e. from 12 % to 70 % (not shown). The central area of Qiyang county was identified with high-risk leaching risk by PSD critical levels from the Qiyang experiment (Fig. 3G). Compared to the risk assessment done with P_{OLSEN}, the PSD-based classification expanded the area for class F_{LOW}, and deceased the high P leaching risk area (Table 5). About 37–85 % more area was recognized into class F_{LOW} when PSD target levels for crop yield were reached compared to the situation when targets (EU-based) for P_{OLSEN} were reached (Table 5). Similar spatial patterns for P_{OLSEN} and PSD were found when only Qiyang targets and limits were used.

4. Discussion

4.1. Use of P_{OLSEN} and P saturation degree to predict crop yield and leaching risks

Both P_{OLSEN} and PSD effectively predicted crop yield and can be used in fertilizer recommendations following the build-up and maintenance approach. They explained 51–95 % of the variation in crop yield with slightly higher values for P_{OLSEN} in the European experiments and slightly higher values for PSD in the Qiyang experiment (Figs. 1 and 2). Similar findings have been found for various crops (Chakraborty and Prasad, 2021; Nair et al., 2004; Renneson et al., 2015). When comparing both soil P tests, P_{OLSEN} limits the optimization of agronomic and environmental aspects since it largely ignores the impact of soil properties on soil P adsorption and soil P buffer capacity driving the spatial

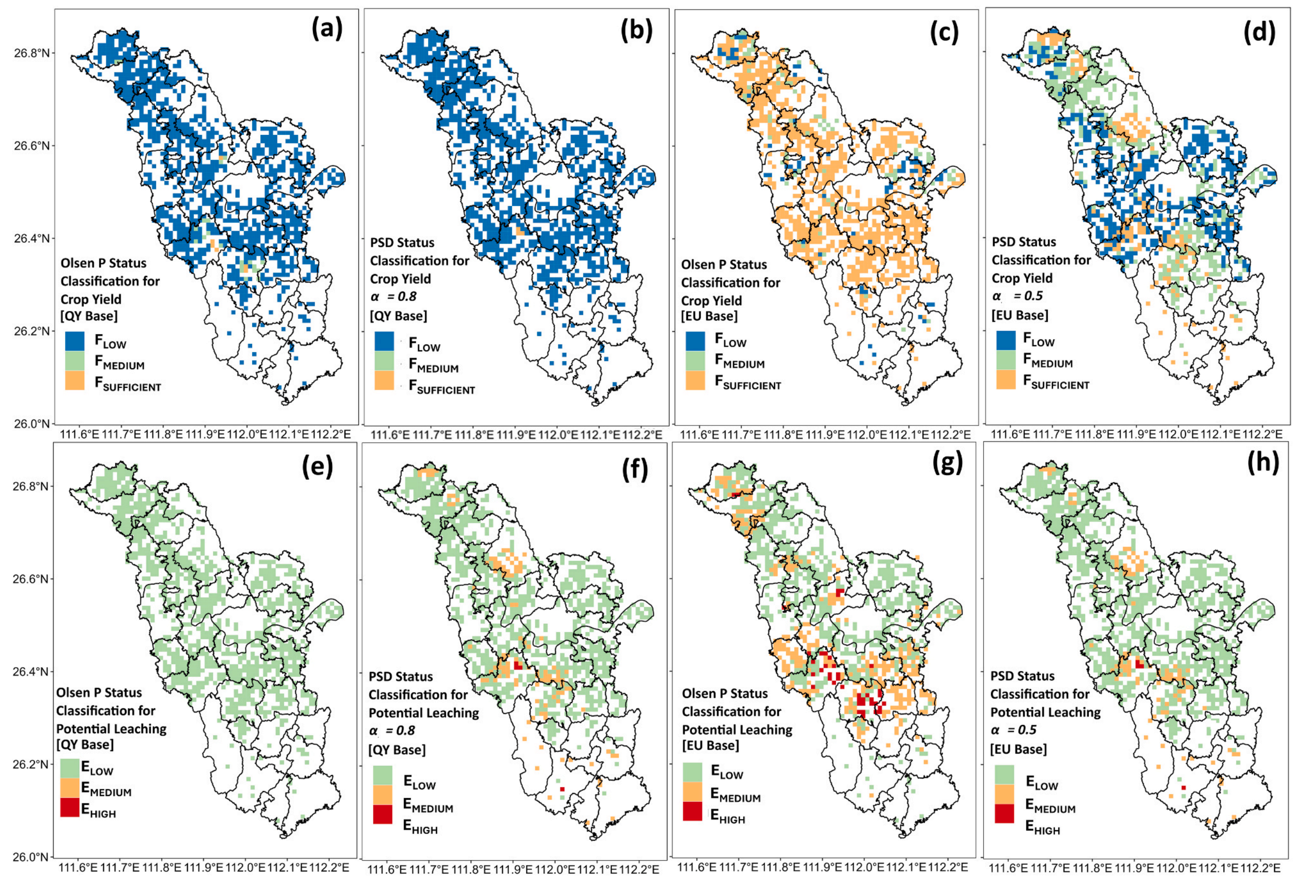

Fig. 3. Spatial variation in soil P status classifications for crop yield (a-d) and potential leaching (e-h) for the Qiyang county: classifications based on P_{OLSEN} or PSD targets for crop yield and critical levels for P losses, derived from the Qiyang experiment (a, b, e and f) and from the European experiments (c, d, g and h) (see Table 2).

Table 5
Soil P status classification (% sites per class) of Qiyang county based on agronomic thresholds (F_{LOW}, F_{MEDIUM}, $F_{SUFFICIENT}$) and environmental thresholds (E_{LOW}, E_{MEDIUM}, E_{HIGH}) derived from both Qiyang and Europe experiments.

	Qiyang		Europe	
Class**	P_{OLSEN}	PSD* (α=0.8)	P_{OLSEN}	PSD (α=0.5)
F_{LOW}	97	100	7	44
F_{MEDIUM}	2.2	0	8.7	39
$F_{SUFFICIENT}$	0.6	<1	84	18
E_{LOW}	-	88	65	89
E_{MEDIUM}	-	12	31	10
E_{HIGH}	-	0.4	4.2	0.4

* if α =0.5 was used to estimate the PSD, then F_{LOW} is 98, F_{MEDIUM} is 1.8, $F_{SUFFICIENT}$ is 0.5, E_{LOW} is 30, E_{MEDIUM} is 66 and E_{HIGH} = 4.

** Class F_{LOW} encompasses all sites where low P availability would lead to a yield smaller than 80 % of the maximum crop yield. Class F_{MEDIUM} represents situations where the crop yield varies between 80 % and 90 % of the maximum yield. Class $F_{SUFFICIENT}$ represents all cases where P is not limiting crop yield. Class E_{LOW} includes all cases where P_{OLSEN} or PSD were lower than 0.5 times a critical threshold (see Table 2), E_{HIGH} all the cases where P_{OLSEN} or PSD exceeds a critical threshold, and the E_{MEDIUM} class all cases in between.

variation in the actual soil P supply for crops (Jordan-Meille et al., 2012).

The P_{OLSEN} target level in the Qiyang experiment needed to reach 90 % of the maximum relative yield (63 mg kg^{-1}) was higher than earlier reported target levels in other Chinese as well European soils, varying mostly between 10 and 25 mg kg^{-1} (Bai et al., 2013; Tang et al., 2009; Van Doorn et al., 2024). The soils in Qiyang are acidic but the pH values are not that low that the $NaHCO_3$ extraction method would lose it efficiency to determine the plant available reactie P pool (Olsen and Watanabe, 1957). Abundant Al_{OX} and Fe_{OX} in the Qiyang experiment increasing soil P adsorption and decreasing P use efficiency might have contributed to the high target P_{OLSEN} level (Wu et al., 2020). Since the relationship between crop response and P addition have been shown to greatly vary between soils for P_{OLSEN} since it ignores the variation in P sorption capacity (Tandy et al., 2021; Zheng, 2024), the use of PSD is often advocated as a valuable replacement.Using the α value of 0.8 for the Qiyang experiment reduces the difference between the target levels for crop yield of the European and Chinese experiments, suggesting that pedogenetic factors, such as parent material, topography and climate, requires a correction for the actual P retention capacity when using PSD at regional scale. Soils with higher effective PSC requires more fertilizer P for crop uptake than soils with lower PSC, which is consistent with previous findings (Wang et al., 2015). For the comparison of the target levels of PSD in different studies as well the derivation of the α value, it is crucial to consider the influence of different extraction methodologies used. In the Qiyang long-term field experiment, the P_{OX} was determined via a soil extraction with 0.175 M ammonium oxalate (McKeague and Day, 1966), while 0.2 M ammonium oxalate was used in the European field experiments (Schwertmann, 1964) whereas in both cases the P concentration was determined via ICP-OES. Given the slightly acidic soil in Qiyang (pH of 5.7), this small difference in molarity is not likely to bridge the differences in target levels between Qiyang and the European field experiments. In addition, the soil extraction with oxalate might include some organic P, in particular in the treatments fertilized with manure. This may have contributed to the variation in P_{OX} and PSD at the higher end but it has limited impact on the target P value. The target levels for both PSD as P_{OLSEN} found in the Qiyang site are much higher than those in European experiments and also higher than other studies done in China, suggesting that this site is not representative for Chinese soils. Through regional sampling, Renneson et al. (2015)reported that a PSD of 0.2–0.3 is required for optimal crop yields, while extrapolating one-point short-term isotherm studies in the laboratory to the field situation, being similar to the threshold range for the Chinese experiments after calibrating α (Table 2). However, the range reported in target values by Renneson et al. (2015) may have been affected by the extrapolation of lab-based research to the field situation (Siatwiinda, 2023). Given the similar patterns observed for PSD in predicting crop yields in Chinese and European experiments after calibrating α (Fig. 2), the target value for PSD might well vary somewhere between 0.1 and 0.3. More insight in target PSD values could be gained from a series of lab and field experiment for various soil and cropping systems. The methodology used to measure P content in the extract, such as colorimetric analysis or ICP-OES, may partially contribute to this discrepancy.

As long as a broad range of soils with various soil properties is included in deriving the underlying relationship with P_{CACL2}, both P_{OLSEN} and PSD can be used as indicators to classify soils as being sensitive to leaching concerning potential losses of P. When only data from Qiyang were used, there was no significant relationship between P_{OLSEN} and P_{CACL2}. In addition, focusing on the European experiments, substantially higher uncertainty is found in the lower ranges of the measured P_{OLSEN} than PSD. In addition, considering the impact of PSC on P leaching, applying the European relationship of P_{CACL2} vs. P_{OLSEN} to soils with higher PSC soils in Qiyang (Tables 1 and 3) might overestimate the leaching risk of P. This may explain why the relationship between P_{CACL2} and P_{OLSEN} in the Qiyang experiment was insignificant (Fig. 2).

A critical value of 20 % PSD has been identified for the P leaching risks in sandy soils, where low levels of Fe_{OX} and Al_{OX} (Nair et al., 2004) makes the soil sentitive to leaching. The critical value found in this study shows a comparable range varying between 20 % and 33 %. Given the influence of PSC on dissolved P in soil P solution and similar critical P_{CACL2} values found for P_{OLSEN} and PSD (2.24 vs 2.55 mg P kg^{-1}), PSD seems a valid soil P test to assess the potential leaching risk. In addition, Pizzeghello et al. (2011) showed that PSD can better reflect the changes in dissolved P concentration than a single agronomic SPT in lab experiments. Note that the detected increase rate in P_{CACL2} beyond the PSD change point was higher in European sites compared to the Qiyang site. The higher increase in P_{CACL2} per unit PSD above the change point suggests that the risk of P losses by leaching increases much faster in European soils once the change point of PSD has surpassed, though part of this difference might be due to the shorter extraction time, lower solution-soil ratio and the molybdate reactive fraction being measured in the extraction method (Fisher et al., 1998; Wünscher et al., 2013) applied in the Chinese experiment.

Similar to the measurement of P_{OX}, differences in methodology affect the differences observed in P_{CACL2} and its correlation with other P indicators. In the Qiyang experiment, P_{CACL2} was determined using a soil-to-solution ratio of 1:5 and shaking for 15 minutes (followed by a P analysis using Murphy-Riley) whereas P_{CACL2} in the European field experiments was determined using a soil-to-solution ratio of 1:10 and a shaking time of 120 minutes (followed by a P analysis using ICP). The longer shaking time and wider soil-to-solution ratio might have led to higher P_{CACL2} concentrations (Barrow and Shaw, 1979; Chapman et al., 2008; Fuhrman et al., 2005) though this impact for extraction time was not found by Sanchez-Alcala et al. (2014). The difference due to P analysis method is small for P_{CACL2} (a bias of 1 % and offset of 0.16 mg kg^{-1}, Wüncher, 2013) but can be substantial for P_{OLSEN} (a bias of 7 % and offset of 4.2 mg kg^{-1}, Wüncher, 2013). These differences, however, are not expected to significantly change the overall patterns observed when relating PSD and P_{OLSEN} to the variation in P_{CACL2} (Figs. 1 and 2), considering that the changes induced by the analysis method linearly affect P_{CACL2}, P_{OLSEN}, and PSD. Note that all soils from the long-term experiments have been stored multiple years before analysis. Storage conditions (such as temperature and humidity) and durations may influence P transformations, and subsequently the size of the extracted P pools, in particular when the storage temperature exceeds 20 degrees (Houba and Novozamsky, 1998). When tested for air-dried soils, Ehlert et al. (2019) showed, however, that storage did not cause a change in soil P test values for soil samples taken from 1958 to 2008.

An ideal soil P test can assess soil P status for both agricultural benefits and the risk of potential P losses. However, environmental critical levels for these SPT are not necessarily higher than the target levels for maximizing crop yield (Bai et al., 2013; Withers et al., 2017), suggesting that agronomic and environmental benefits cannot be achieved simultaneously in all cases. In the current study, the critical level for European soils was higher than the agronomic target value showing that fertilizer practices guided by the PSD would be beneficial for the aquatic environment as well. In contrast, the critical level from the Qiyang experiment was lower than the agronomic target level for crop yield. This could be due to the binding capacity of the soil, where even at high P_{OX} levels, only a limited amount of P is available in the soil solution, leading to higher target levels desired for crop yield. Given the uncertainty on the critical limit as being derived via the split line algorithm, additional data from long-term studies or regional soil assessments are needed to underpin this for soils having high PSC. Specifically, using the critical P_{CACL2} concentration found in European datasets with substantial variation in soil properties, being estimated at 2.24 mg kg^{-1}, critical values for Qiyang would be around 30 % for PSD ($\alpha = 0.8$) being almost equal to the agronomic target value. The fact that environmental critical levels might be reached before reaching the agronomic target has been indicated earlier by Withers et al. (2017), who noted that if a demanding P concentration were established for the environment (e.g., 30–35 ug L^{-1} to prevent algal growth), agricultural target levels would not be achieved. In that case, the estimated environmental P_{CACL2} levels at critical PSD (0.87 mg P kg^{-1} being equal to about 0.087 mg P L^{-1}) are substantially lower than the Environmental quality standards for surface water in China (type V, 0.4 mg P L^{-1}, irrigation water). Recalculating backwards, a critical P_{CACL2} level of 4 mg kg^{-1} would imply a critical PSD for water quality around 60 % when using the observations from Qiyang experiment and a critical PSD around 40 % when observations from European experiments were used (Fig. 2). In that case, the agronomic target values remain below the critical values for water quality, implying that no substantial P risk losses occur when soils are fertilized given a build-up and maintenance approach (Bai et al., 2013; Jordan-Meille et al., 2012).

4.2. *Implications of using P saturation degree instead of P_{OLSEN} for regional P fertilization*

The use of P_{OLSEN} in fertilizer recommendation systems might overestimate the soil P supply Considering the agronomic P_{OLSEN} and PSD targets based on the multiple European experiments, the cropland area in Qiyang was classified as being sufficient in 84 % of the cases when P_{OLSEN} was used whereas 83 % was classified as low and medium when PSD was used (Table 5). This implies that the required P dose to sustain high crop yields might be underestimated by P_{OLSEN}, in particular for areas with high P_{OLSEN} and low PSD, assuming the same target level should be achieved. Assuming that the required P dose is equally allocated over the three P fertility classes used for both soil P tests, and using the recommended P rates from Li et al. (2011) for the classes $F_{SUFFICIENT}$ (17.5 kg P ha^{-1}), F_{MEDIUM} (35 kg P ha^{-1}), and F_{LOW} (48 kg P ha^{-1}), a shift from P_{OLSEN} to PSD would increase the averaged P requirement over the county from 21 to 38 kg P ha^{-1}, implying an annual increase in P inputs of 45 %. Additional field observations in Qiyang are needed to delineate zones with contrasting insights regarding the soil P availability as being determined with both soil P tests. Additionally, the lower variation in target PSD levels derived from five experiments compared to

P_{OLSEN} (-33 %, Table 3) suggested that PSD is more generally applicable for defining target P levels for optimum crop yield at regional level. Given the natural variability in soil properties as well the fact that the PSD also provides mechanistic insights in the fate of P in soil, the classification of the soil P status following the PSD assessment is more likely to guide sustainable P use in agriculture. Unlike the European-based evaluation, the use of P_{OLSEN} or PSD did not distinctly affect soil P classifications if target levels from the Qiyang experiment were applied (Table 5), mainly due to the unrealistic high target values observed in this single field experiment.

Using PSD to classify the risk for P leaching instead of P_{OLSEN} decreased the area with moderate and high risk (classes E_{MEDIUM} and E_{HIGH}) by 25 % (Table 5). This demonstrated that high P_{OLSEN} levels do not always induce P loss, and that variation in PSC should be taken into account when managing P for environmental protection at the regional level. Soils with high P_{OLSEN} but low PSD levels can pose a lower risk due to higher P retention via sorption of P on Fe_{OX} and Al_{OX} (Blombäck et al., 2021). While the PSD has mainly been used for environmental risk assessment due to its relationship with P intensity methods like P_{CACL2} or P_{OLSEN}, this study showed that the PSD also underpins the actual crop response to P fertilization. Since PSD provides insights in the total reversible bound P by both the maximum P sorption capacity and the extent to which the sorption sites are loaded with P it indirectly corrects for impacts of site conditions controlling the fate of P in soil (De Campos et al., 2018; Fischer et al., 2017). Earlier studies also showed that soils with the same soil test P level but with different mineralogy or pH levels can show varying P concentrations in soil solution (Pizzeghello et al., 2011). The inclusion of maximum P sorption capacity in PSD is particularly relevant since it allows to predict long terms response of reversibly bound P to P inputs with related impacts on crop P uptake and P losses to groundwater and surface water (Van Doorn et al., 2024). Instead of using single soil P test, many countries, including the Netherlands, Germany, and Canada, therefore already assess potential P loss risks by PSD rather than an agronomic soil P tests at a regional level (Fischer et al., 2017; Schoumans and Chardon, 2015; Wang et al., 2016). Soils with high PSD levels should therefore be mined to avoid high P leaching to surface waters.

4.3. Uncertainties in the regional dependent α value

Even though PSD is frequently employed for managing regional environmental P (Fischer et al., 2017), the PSC as well as the fraction of these oxides that can adsorb P have impacts on the classification of the soil P fertility status. Adjusting the α value from 0.5 to 0.8 decreased the total area with high and moderate leaching risks by 48 % (Table 5), corresponding to a slight increase in P deficiencies for crop yields (Fig. 3c). As a consequence, more P input is needed to sustain crop production. This suggests that regional dependent α values might be needed to define sustainable regional P strategies, since regions show differences in pedogenetic factors regulating the binding capacity of PSC. Different α values have been found for different climate zones in literature (being summarized in Table S1), decreasing from 0.8 in tropical regions, 0.5 in subtropical regions down to 0.4 in temperate regions (Figure S3) confirming that substantial variation in P sorption occur across regions that differ in pedogenesis factors. This finding is consistent with the hypothesis that highly weathered soils in tropical regions induce the formation of crystalline oxides or other minerals that contribute to PSC (De Campos et al., 2018). This can be explained by increased weathering in tropical and subtropical locations, which reduces soil particle size and raises the soil specific surface area (Wang et al., 2013). In addition, both incubation experiments and model calculations in Chinese soils showed that clay minerals including goethite, kaolinite, and illite, are as important as amorphous Fe and Al oxides in subtropical soils regarding the retention of P, which can also partly explain the higher α being applied in Qiyang (Xiong et al., 2022). Therefore, parameterizing α value based on region-specific weathering, climate conditions, and other factors related to pedogenesis is relevant to enhance the use of PSD across various regions globally.

4.4. Research outlook

Applying a PSD-based soil P classification for crop yield and potential leaching risks has important implications for sustainable regional P management. The implicit assumption of the build-up and maintenance approach is that adjusting the P inputs to the soil P status ensures sustainable P use and thereby improves P use efficiency. In line with the published critical soil P values, the target levels for PSD in the current analysis of European experiments are lower than the critical levels desired to minimize the risk of P leaching (Bai et al., 2013). The acceptability of P leaching losses at a target level for crop yield depends on its contribution to P inputs into surface water. In most cases, other sources—such as erosion, surface runoff from agricultural soils, inputs from non-agricultural soils, aquaculture, and wastewater point sources—dominate P inputs to surface water (Beusen et al., 2022). This suggests that fertilization up to a change point, and possibly even beyond, may not significantly affect P delivery to surface waters. However, locally, the contribution of P leaching can be substantial, and even fertilization below the change point for P leaching can pose risks, suggesting that the optimal P amount for target yield and low environmental risk can be achieved simultaneously. However, the target levels for crop yield may exceed the critical levels for P leaching, as shown in the Qiyang experiment, indicating a trade-off between crop production and environmental protection, particularly in regions with strict environmental limits (Withers et al., 2017). Additional experimental P data from soils of similar agroecosystems may be necessary to confirm this finding, as the Qiyang results are from a single site, while the European target and critical levels include multiple experiments. In addition to soil test P level (e.g., P_{OLSEN}), P index (e.g., PSD) and soil properties, the precipitation surplus and hydrological connectivity can also increase the quantities of P leached from soils (Xue et al., 2013). Therefore, sustainable P management should not rely only on optimizing required P input alone but also evaluating the impacts of other factors, including climate and hydrologic factors, which affect the transport of P from the soil to surrounding water body (Wang et al., 2022).

To expand the applicability of PSD for regional P management across various climatic regions and soil pedogenesis conditions, it would be highly beneficial to develop a pedotransfer function that relates the α value to commonly used soil properties related to P dynamics, especially for heterogeneous soils (Beck et al., 2004). In addition, existing spatially explicit datasets for basic soil properties and P levels determined using classic soil P tests such as P_{OLSEN} or $P_{MEHLICH3}$ could be leveraged by using empirical relationships to translate the soil P value to P_{OX} and converting soil mineralogy to levels of Fe_{OX} and Al_{OX} determining the P retention capacity (Khaledian et al., 2018). PSD provides an advantage over classic soil P tests because it also provides insight into the effect of fertilization on the change in soil P and the time at which target levels are met. Special attention is required when applying PSD at the regional level, as the presence of carbonates in calcareous soils can affect the measurement of Al_{OX}, Fe_{OX} and P_{OX}, thereby affecting PSD. Theoretically, simple mass balance approaches can be used with the measured values for P_{OX}, Al_{OX} and Fe_{OX} to estimate the time span required to meet agri-environmental targets given a certain P balance, assuming instantaneous equilibrium between soil P pools and P fertilizers added. However, it is worth noting that PSD and other P indicators reach their maximum levels when soil P surplus is around 3200 kg P ha^{-1} (Gu et al., 2023), meaning that continually excessive P input may not elevate soil P levels once soils are P saturated.

In addition, although many countries or regions apply P_{CACL2} as an indicator to characterize environmental risk, it should be noted that actual P losses also occur via erosion and subsurface runoff, which further depend on hydrology and topography conditions (Schoumans and Chardon, 2015). Therefore, regional insights on the predominant pathways are required to achieve more accurate P management at the regional level to avoid unnecessary P export to groundwater and surface water (Goyette et al., 2018).

5. Conclusions

Long-term field experiments conducted in Qiyang and Europe showed that the variation in crop yield and potential P leaching losses is comparably explained by PSD and P_{OLSEN}. Considering the benefits of PSD above P_{OLSEN}, i.e. inclusion of the total pool of reversibly bound P acting as a reserve for plant-available P and of the maximum soil P sorption capacity, the PSD thus outcompetes P_{OLSEN} as a soil P test to optimize P management. More research is, however, is needed on the location of target levels and critical levels for PSD in view of crop yields and P leaching risk, especially with respect to the factors controlling the α value, which strongly affects the derived PSD.

We found that the critical level of PSD to minimize P leaching risks was higher than the target level required for crop yield in the European experiments, implying that P fertilizer management up to a target level for crop yields will not lead to strongly enhanced P leaching losses. The target level for crop yields when using a cut-off point at 90 % of the maximum relative yield and an α value of 0.8 (0.31), was higher than the critical PSD level to avoid substantial P leaching (0.20) in the Qiyang experiment. However, the target PSD level is likely not representative for Chinese soils, considering that the target P_{OLSEN} level for crop yields in the experiment was very high (63 mg kg^{-1}) compared to literature data for China. Instead, the European experiments seem more representative, considering that the target P_{OLSEN} level for crop yields (10 mg kg^{-1}) compares much better with literature data for China. When using the results for the European experiments, the target PSD levels for crop yield were always lower than those for the risk of P leaching. Applying the European derived target levels and critical for P_{OLSEN} on Qiyang county thus causes a lower area of P deficient soils and a higher area being sensitive to P leaching losses as compared to the use of target and critical PSD levels. Applying a regional dependent α value for PSC allows the derivation of comparable critical target levels of PSD for crop yield across European and Chinese experiments. As such, the PSD can improve P management on local and regional scales. However, the experimental data challenge the assumption that P fertilizer management up to a target level for crop yields will always lead to situations with low P leaching losses, suggesting that both agronomy and environment can be conflicting in view of P strategies.

CRediT authorship contribution statement

Jianbo Shen: Writing – review & editing, Supervision, Funding acquisition. **Zejiang Cai:** Investigation. **Minggang Xu:** Data curation. **Wim de Vries:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Qichao Zhu:** Writing – review & editing, Supervision. **Maarten van Doorn:** Writing – review & editing. **Yu Gu:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Gerard H. Ros:** Writing – review & editing, Formal analysis, Conceptualization.

Declaration of Competing Interest

We declare that there are no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (32130094), the National Key Research and Development Program of China (2023YFD1901502), the Hainan Provincial Natural Science Foundation of China (321CXTD443), Yunnan Provincial Science and Technology Plan Project (202102AE090030), the 2115 Talent Development Program of China Agricultural University, the Yunnan Science and Technology Department project "Yunnan Modern Agricultural Green Technology Innovation Platform (202102AE090053)", Project of New Fertilizer Research and Development of Yun-Tian-Hua Group of Yunnan of China (YTH-4320-WB-FW-2021-031303-00), China Scholarship Council (No. 201913043) and Hainan University. The authors also acknowledge several researchers for sharing their data on crop yields and the phosphorus saturation degree gathered in long-term field experiments. Specifically, we thank Gunnar Börjesson of the Swedish University of Agricultural Sciences (site Lanna), Bettina Eichler-Löbermann of the University of Rostock (site Rostock), Steve McGrath of Rothamsted Research (sites Rothamsted, Saxmundham, Peldon and Great Carlton), Pascal Denoroy, Claire Jouany and Sylvain Pellerin of the French National Institute for Agriculture, Food, and Environment (sites Pierroton, Toulouse and Carcares), Bruno Huyghebaert of the Walloon Agricultural Research Centre (site Gembloux) and Annemie Elsen of the Soil Service of Belgium research & Development (site Ath) and, Erik Smolders of the Faculty of Bioscience Engineering of the Catholic University of Leuven.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127347.

References

Amery, F., Vandecasteele, B., D'Hose, T., Nawara, S., Elsen, A., Odeurs, W., Vandendriessche, H., Arlotti, D., McGrath, S.P., Cougnon, M., Smolders, E., 2021. Dynamics of soil phosphorus measured by ammonium lactate extraction as a function of the soil phosphorus balance and soil properties. Geoderma 385, 114855. https://doi.org/10.1016/j.geoderma.2020.114855.

Bai, Z.H., Li, H.G., Yang, X.Y., Zhou, B.K., Shi, X.J., Wang, B.R., Li, D.C., Shen, J.B., Chen, Q., Qin, W., Oenema, O., Zhang, F.S., 2013. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant Soil *372* (1-2), 27–37. https://doi.org/10.1007/s11104-013-1696-y.

Bao, S., 2000. Soil agrochemical analysis, 67. China Agricultural Press, Beijing, p. 72 (in Chinese).

Barrow, N., Shaw, T., 1979. Effects of solution: soil ratio and vigour of shaking on the rate of phosphate adsorption by soil. J. Soil Sci. 30 (1), 67–76. https://doi.org/10.1111/j.1365-2389.1979.tb00965.x.

Beauchemin, S., Simard, R., 1999. Soil phosphorus saturation degree: Review of some indices and their suitability for P management in Quebec, Canada. Can. J. Soil Sci. 79, 615–625. https://doi.org/10.4141/S98-087.

Beck, M.A., Zelazny, L.W., Daniels, W.L., Mullins, G.L., 2004. Using the Mehlich-1 Extract to Estimate Soil Phosphorus Saturation for Environmental Risk Assessment. *Soil Sci. Soc. Am. J.*68(5) 1762–1771. https://doi.org/10.2136/sssaj2004.1762.

Beusen, A.H.W., Doelman, J.C., Van Beek, L.P.H., Van Puijenbroek, P.J.T.M., Mogollón, J.M., Van Grinsven, H.J.M., Stehfest, E., Van Vuuren, D.P., Bouwman, A. F., 2022. Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways. Glob. Environ. Change 72. https://doi.org/10.1016/j.gloenvcha.2021.102426.

Blombäck, K., Bolster, C.H., Lindsjö, A., Hesse, K., Linefur, H., Parvage, M.M., 2021. Comparing measures for determination of phosphorus saturation as a method to estimate dissolved P in soil solution. Geoderma 383, 114708. https://doi.org/10.1016/j.geoderma.2020.114708.

Cai, Z., Wang, B., Xu, M., Zhang, H., He, X., Zhang, L., Gao, S., 2014. Intensified soil acidification from chemical N fertilization and prevention by manure in an 18-year field experiment in the red soil of southern China. J. Soils Sediment. 15 (2), 260–270. https://doi.org/10.1007/s11368-014-0989-y.

Chakraborty, D., Prasad, R., 2021. Stratification of soil phosphorus forms from long-term repeated poultry litter applications and its environmental implication. Environ. Chall. 5, 100374 https://doi.org/10.1016/j.envc.2021.100374.

Chapman, P.J., Edwards, A.C., Shand, C.A., 2008. The phosphorus composition of soil solutions and soil leachates: Influence of soil:solution ratio. Eur. J. Soil Sci. 48 (4), 703–710. https://doi.org/10.1111/j.1365-2389.1997.tb00570.x.

Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. Glob. Environ. Change 19 (2), 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009.

De Campos, M., Antonangelo, J.A., Van der Zee, S.E., Alleoni, L.R.F., 2018. Degree of phosphate saturation in highly weathered tropical soils. Agric. Water Manag 206, 135–146, 206, 135-146.

Ehlert P., Reijneveld, J.A., Oenema, O., 2019. Phosphorus fertilization recommendations for potato based on a combined soil test indicator. Abstract submitted to ISSPA conference at Wageningen.

Fischer, P., Pothig, R., Venohr, M., 2017. The degree of phosphorus saturation of agricultural soils in Germany: current and future risk of diffuse P loss and implications for soil P management in Europe. Sci. Total Environ. 599-600, 1130–1139. https://doi.org/10.1016/j.scitotenv.2017.03.143.

Fisher, E., Thornton, B., Hudson, G., Edwards, A.C., 1998. The variability in total and extractable soil phosphorus under a grazed pasture. Plant Soil 203, 249–255.

Fuhrman, J., Zhang, H., Schroder, J., Davis, R., Payton, M., 2005. Water-soluble phosphorus as affected by soil to extractant ratios, extraction times, and electrolyte. Commun. Soil Sci. Plant Anal. 36 (7-8), 925–935. https://doi.org/10.1081/CSS-200049482.

Gilbert, N., 2009. Environment: The disappearing nutrient. Nature 461 (7265), 716–718. https://doi.org/10.1038/461716a.

Goyette, J.O., Bennett, E.M., Maranger, R., 2018. Low buffering capacity and slow recovery of anthropogenic phosphorus pollution in watersheds. Nat. Geosci. 11 (12), 921–925. https://doi.org/10.1038/s41561-018-0238-x.

Gu, Y., Ros, G.H., Zhu, Q., Zheng, D., Shen, J., Cai, Z., Xu, M., De Vries, W., 2023. Responses of total, reactive and dissolved phosphorus pools and crop yields to long-term fertilization. Agric., Ecosyst. Environ. 357, 108658. https://doi.org/10.1016/j.agee.2023.108658.

Houba, V.J.G., Novozamsky, I., 1998. Influence of storage time and temperature of air-dried soils on pH and extractable nutrients using 0.01 mol/L CaCl2. Fresenius' J. Anal. Chem. 360 (3), 362–365. https://doi.org/10.1007/s002160050712.

Jordan-Meille, L., Rubaek, G.H., Ehlert, P.A.I., Genot, V., Hofman, G., Goulding, K., Recknagel, J., Provolo, G., Barraclough, P., 2012. An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. Soil Use Manag 28 (4), 419–435. https://doi.org/10.1111/j.1475-2743.2012.00453.x.

Khaledian, Y., Quinton, J.N., Brevik, E.C., Pereira, P., Zeraatpisheh, M., 2018. Developing global pedotransfer functions to estimate available soil phosphorus. Sci. Total Environ. 644, 1110–1116. https://doi.org/10.1016/j.scitotenv.2018.06.394.

Liu, X., Sheng, H., Jiang, S., Yuan, Z., Zhang, C., Elser, J.J., 2016. Intensification of phosphorus cycling in China since the 1600s. Proc. Natl. Acad. Sci. 113 (10), 2609–2614. https://doi.org/10.1073/pnas.1519554113.

Lookman, R., Jansen, K., Merckx, R., Vlassak, K., 1996. Relationship between soil properties and phosphate saturation parameters a transect study in northern Belgium. Geoderma 69 (3-4), 265–274. https://doi.org/10.1016/0016-7061(95)00068-2.

McDowell, R.W., Pletnyakov, P., Haygarth, P.M., 2024. Phosphorus applications adjusted to optimal crop yields can help sustain global phosphorus reserves. Nat. Food. https://doi.org/10.1038/s43016-024-00952-9.

McKeague, J., Day, J., 1966. Dithionite-and oxalate-extractable Fe and Al as aids in differentiating various classes of soils. Can. J. Soil Sci. 46 (1), 13–22. https://doi.org/10.4141/cjss66-003.

Møller, A.B., Heckrath, G., Hermansen, C., Nørgaard, T., de Jonge, L.W., Greve, M.H., 2023. Mapping the phosphorus sorption capacity of Danish soils in four depths with quantile regression forests and uncertainty propagation. Geoderma 430. https://doi.org/10.1016/j.geoderma.2022.116316.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36. https://doi.org/10.1016/S0003-2670(00)88444-5.

Nair, V.D., Portier, K.M., Graetz, D.A., Walker, M., 2004. An environmental threshold for degree of phosphorus saturation in sandy soils. J. Environ. Qual. 33 (1), 107–113. https://doi.org/10.2134/jeq2004.1070.

Nawara, S., Van Dael, T., Merckx, R., Amery, F., Elsen, A., Odeurs, W., Vandendriessche, H., Mcgrath, S., Roisin, C., Jouany, C., Pellerin, S., Denoroy, P., Eichler-Lobermann, B., Borjesson, G., Goos, P., Akkermans, W., Smolders, E., 2017. Eur. J. Soil Sci. 68 (6), 873–885. https://doi.org/10.1111/ejss.12486.

Olsen, S.R., Watanabe, F.S., 1957. A method to determine a phosphorus adsorption maximum of soils as measured by the Langmuir isotherm. Soil Sci. Soc. Am. J. 21 (2), 144–149.

Pizzeghello, D., Berti, A., Nardi, S., Morari, F., 2011. Phosphorus forms and P-sorption properties in three alkaline soils after long-term mineral and manure applications in north-eastern Italy. Agric. Ecosyst. Environ. 141 (1-2), 58–66. https://doi.org/10.1016/j.agee.2011.02.011.

Renneson, M., Vandenberghe, C., Dufey, J., Marcoen, J.M., Bock, L., Colinet, G., 2015. Degree of phosphorus saturation in agricultural loamy soils with a near-neutral pH. Eur. J. Soil Sci. 66 (1), 33–41. https://doi.org/10.1111/ejss.12207.

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Armstrong McKay, D.I., Bai, X., Bala, G., Bunn, S.E., 2023. Safe and just Earth system boundaries. Nature 1–10. https://doi.org/10.1038/s41586-023-06083-8.

Schoumans, O.F., Chardon, W.J., 2015. Phosphate saturation degree and accumulation of phosphate in various soil types in The Netherlands. Geoderma 237, 325–335. https://doi.org/10.1016/j.geoderma.2014.08.015.

Schwertmann, U., 1964a. Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung. Z. F. üR. Pflanz. ährung, D. üngung, Bodenkd. *105* (*3*), 194–202. https://doi.org/10.1002/jpln.3591050303.

Sharpley, A.N., Brye, K.R., Burke, J.M., Berry, L.G., Daniels, M.B., Webb, P., 2020. Can soil phosphorus sorption saturation estimate future potential legacy phosphorus sources? Agrosystems, Geosci. Environ. 3 (1) https://doi.org/10.1002/agg2.20122.

Siatwiinda, S.M., 2023. Using model-based and experimental multi-nutrient approaches to improve fertilization recommendations for maize in Zambia (Doctoral dissertation). Wageningen Univeristy. ⟨https://www.wur.nl/en/publication-details.htm?publicationId=publication-way-363137393337⟩ (Doctoral dissertation).

Siatwiinda, S.M., Ros, G.H., Yerokun, O.A., De Vries, W., 2024. Options to reduce ranges in critical soil nutrient levels used in fertilizer recommendations by accounting for site conditions and methodology: A review. Agron. Sustain. Dev. 44 (1), 9. https://doi.org/10.1007/s13593-023-00943-3.

Smit, A.L., Bindraban, P.S., Schröder, J., Conijn, J., Van der Meer, H., 2009. Phosphorus in agriculture: global resoources, trends and developments: report to the Steering Committee Technology Assessment of the Ministery of Agriculture, Nature and Food Quality, The Netherlands, and in collaboration with the Nutrient Flow Task Group (NFTG), supported by DPRN (Development Policy review Network). 1566-7790. Plant Res. Int. ⟨https://library.wur.nl/WebQuery/wurpubs/383557⟩.

Springmann, M., Clark, M., Mason-D′Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., De Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockstrom, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562 (7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347 (6223), 1259855. ⟨https://www.science.org/doi/10.1126/science⟩.

Tandy, S., Hawkins, J.M.B., Dunham, S.J., Hernandez-Allica, J., Granger, S.J., Yuan, H., McGrath, S.P., Blackwell, M.S.A., 2021. Investigation of the soil properties that affect Olsen P critical values in different soil types and impact on P fertiliser recommendations. Eur. J. Soil Sci. 72 (4), 1802–1816. https://doi.org/10.1111/ejss.13082.

Tang, X., Ma, Y.B., Hao, X.Y., Li, X.Y., Li, J.M., Huang, S.M., Yang, X.Y., 2009. Determining critical values of soil Olsen-P for maize and winter wheat from long-term experiments in China. Plant Soil 323 (1-2), 143–151.

Van der Zee, S., Fokkink, vd, LGJ, Van Riemsdijk, W., 1987. A new technique for assessment of reversibly adsorbed phosphate. Soil Sci. Soc. Am. J. 51 (3), 599–604. https://doi.org/10.2136/sssaj1987.03615995005100030009x.

Van Doorn, M., Van Rotterdam, D., Ros, G., Koopmans, G.F., Smolders, E., De Vries, W., 2024. The phosphorus saturation degree as a universal agronomic and environmental soil P test. Crit. Rev. Environ. Sci. Technol. 54 (5), 385–404.

Van Rotterdam, A.M.D., Bussink, D.W., Temminghoff, E.J.M., van Riemsdijk, W.H., 2012. Predicting the potential of soils to supply phosphorus by integrating soil chemical processes and standard soil tests. Geoderma 189-190, 617–626.

Wang, X., Li, W., Harrington, R., Liu, F., Parise, J.B., Feng, X., Sparks, D.L., 2013. Effect of ferrihydrite crystallite size on phosphate adsorption reactivity. Environ. Sci. Technol. 47 (18), 10322–10331. https://doi.org/10.1021/es401301z.

Wang, Y.P., Huang, Y., Augusto, L., Goll, D.S., Helfenstein, J., Hou, E., 2022. Toward a Global Model for Soil Inorganic Phosphorus Dynamics: Dependence of Exchange Kinetics and Soil Bioavailability on Soil Physicochemical Properties. Glob. Biogeochem. Cycle 36 (3). https://doi.org/10.1029/2021GB007061.

Wang, Y.T., Zhang, T.Q., O'Halloran, I.P., Hu, Q.C., Tan, C.S., Speranzini, D., Macdonald, I., Patterson, G., 2015. Agronomic and environmental soil phosphorus tests for predicting potential phosphorus loss from Ontario soils. Geoderma 241-242, 51–58. https://doi.org/10.1016/j.geoderma.2014.11.001.

Wang, Y.T., Zhang, T.Q., O'Halloran, I.P., Tan, C.S., Hu, Q., 2016. A phosphorus sorption index and its use to estimate leaching of dissolved phosphorus from agricultural soils in Ontario. Geoderma 274, 79–87. https://doi.org/10.1016/j.geoderma.2016.04.002.

Withers, P.J.A., Hodgkinson, R.A., Rollett, A., Dyer, C., Dils, R., Collins, A.L., Bilsborrow, P.E., Bailey, G., Sylvester-Bradley, R., 2017. Reducing soil phosphorus fertility brings potential long-term environmental gains: a UK analysis. Environ. Res. Lett. 12 (6). ⟨https://iopscience.iop.org/article/10.1088/1748-9326/aa69fc/meta⟩.

Wu, Q., Zhang, S., Feng, G., Zhu, P., Huang, S., Wang, B., Xu, M., 2020. Determining the optimum range of soil Olsen P for high P use efficiency, crop yield, and soil fertility in three typical cropland soils. Pedosphere 30 (6), 832–843. https://doi.org/10.1016/S1002-0160(20)60040-6.

Wünscher, R., Unterfrauner, H., Peticzka, R., Zehetner, F., 2013. A comparison of different phosphorus extraction methods with the phosphorus uptake of wheat. na.

Xiong, J., Liu, Z., Yan, Y., Xu, J., Liu, D., Tan, W., Feng, X., 2022. Role of clay minerals in controlling phosphorus availability in a subtropical Alfisol. Geoderma 409. https://doi.org/10.1016/j.geoderma.2021.115592.

Xu, D., Zhu, Q., Ros, G., Cai, Z., Wen, S., Xu, M., Zhang, F., De Vries, W., 2022. Calculation of spatially explicit amounts and intervals of agricultural lime applications at county-level in China. Sci. Total Environ. 806 (Pt 4), 150955 https://doi.org/10.1016/j.scitotenv.2021.150955.

Xue, Q.Y., Dai, P.B., Sun, D.S., Sun, C.L., Qi, L.Y., Ostermann, A., He, Y., Lin, X.Y., 2013. Effects of rainfall and manure application on phosphorus leaching in field lysimeters during fallow season. J. Soils Sediment. 13 (9), 1527–1537. https://doi.org/10.1007/s11368-013-0757-4.

Zhang, W., Tang, X., Feng, X., Wang, E., Li, H., Shen, J., Zhang, F., 2019. Management Strategies to Optimize Soil Phosphorus Utilization and Alleviate Environmental Risk in China. J. Environ. Qual. 48 (5), 1167–1175. https://doi.org/10.2134/jeq2019.02.0054.

Zheng, D., 2024. Soil phosphorus dynamics in response to soil properties and rhizosphere processes. Doctoral dissertation. China Agricultural University.

Zhu, Q., Liu, X., Hao, T., Zeng, M., Shen, J., Zhang, F., De Vries, W., 2020. Cropland acidification increases risk of yield losses and food insecurity in China. Environ. Pollut. 256, 113145 https://doi.org/10.1016/j.envpol.2019.113145.

Zou, T., Zhang, X., Davidson, E.A., 2022. Global trends of cropland phosphorus use and sustainability challenges. Nature 611 (7934), 81–87. https://doi.org/10.1038/s41586-022-05220-z.