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Opportunities for optimizing phosphorus inputs in EU agricultural soils

Elise Van Eynde [a,*], Gerard H. Ros [b], Felipe Yunta [a], Anna Muntwyler [c], Philippe Hinsinger [d], Arthur N. Fendrich [a], Panos Panagos [a]

[a] European Commission, Joint Research Centre (JRC), Ispra, VA, Italy
[b] Earth Systems and Global Change Group, Wageningen University and Research, Wageningen 6700AA, the Netherlands
[c] Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland
[d] Eco&Sols, Univ Montpellier, Cirad, INRAE, Institut Agro, IRD, Montpellier, France

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ABSTRACT

Excessive phosphorus (P) fertilization has resulted in elevated soil P concentrations in some regions in the EU. Legacy soil P imposes a risk for soil functioning and may lead to P losses into the aquatic environment. Recent proposed EU policies aim to optimize P inputs and mitigate excessive soil P concentrations. We present a framework to estimate how much and where P inputs in EU agricultural (cropland and grassland) soils can be optimized. The framework, with assumptions on optimal soil P concentrations and modelled soil P balances, allows calculating how much of the EU agricultural area experiences a build-up or maintenance of soil P concentrations despite having high soil P concentrations. Next, we calculated how much P inputs can be reduced to reach maintenance situation (inputs equal outputs) or to reach optimal soil P concentrations. Assuming optimal soil P concentrations (Olsen) being 20 – 40 mg kg^{-1}, we calculated that current P inputs across the EU can be reduced by 21 % without adverse impacts on crop production, in line with EU policy objectives. The most appropriate strategy strongly depended on the farming system properties and varied across the European regions. The results are discussed in view of current or desired policies limiting P application rates. The framework, with suggested future improvements on uncertainties in data and models, can guide policy makers and land managers to set targets on P application rates, thereby reconciling agronomic and environmental objectives.

1. Introduction

Phosphorus (P) is an essential element for plant growth and is therefore indispensable for food production and security (Johnston, 2000; Magnone et al., 2022). Since 2014, phosphate rock has been identified as a critical raw material in the European Union (EU), given its high economic importance in combination with a high supply-risk due to EU dependency on a limited number of supplying countries (European Commission, 2014). Inappropriate use of P in agriculture should be avoided to increase the resource efficiency of agriculture (de Boer et al., 2018). In addition, recent increase in fertilizer prices has put fertilizer affordability and availability at risk for farmers (Cordell et al., 2009; European Commission, 2022). In addition, the over- and inefficient application of P fertilizers and manure have led to P accumulation in soils, negatively affecting soil functioning such as habitat provision (Ceulemans et al., 2014) and increasing P losses to groundwater and surface water via leaching, runoff and erosion (Sandström et al., 2023). Excess P application in intensive agriculture has been clearly identified as responsible for getting beyond one of the nine planetary boundaries (Steffen et al., 2015). Although P concentrations in EU freshwaters and fluxes to the sea have reduced during the two last decades, concentrations in freshwaters remain above ecological water quality thresholds (Vigiak et al., 2023), threatening the ecological objectives of the Water Framework Directive (European Commission, 2000). The reductions in water P concentrations have been reached mainly due to the elimination of point sources via optimizing sewage treatment plants. However, latest research from monitoring networks shows that the decline in P concentrations is levelling off (European Environment Agency, 2023), similar as the stagnating recovery in ecological diversity in surface waters (Haase et al., 2023). The current exceedances of P calls for future actions to optimize crop, soil and nutrient management to reach the desired chemical and ecological surface water quality in the EU (Vigiak

* Corresponding author.
E-mail addresses: Elise.VAN-EYNDE@ec.europa.eu (E. Van Eynde), gerard.ros@wur.nl (G.H. Ros), Felipe.YUNTA-MEZQUITA@ec.europa.eu (F. Yunta), muntwyler@ifu.baug.ethz.ch (A. Muntwyler), philippe.hinsinger@inrae.fr (P. Hinsinger), Arthur.FENDRICH@ec.europa.eu (A.N. Fendrich), Panos.PANAGOS@ec.europa.eu (P. Panagos).

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et al., 2023).

The European Commission aims to reduce nutrient losses by 50 % and inputs to agricultural land by 20 % by 2030 though, among others, the adoption of balanced fertilization practices (European Commission, 2020). From an agronomic perspective, balanced fertilization implies the adoption of a fertilization strategy where the P application rate is determined by the crop P uptake as well the soil P status (van Doorn et al., 2023).

Besides regulations targeting agricultural land management, the European Commission has proposed the Soil Monitoring and Resilience Law (European Commission, 2023). The proposed directive includes 12 soil descriptors for which criteria for healthy soil conditions have been proposed. For soil P, agricultural soils with P concentrations above a threshold set by Member States, are considered as unhealthy. After approval, the directive will recommend Member States to monitor soils regularly for, among others, P concentrations and adapt management strategies to reach a healthy status in all soils by 2050.

These recent and foreseen policy developments to reduce the environmental impact of P call for an evaluation of current P management in relation to target soil P levels in the EU, and for a framework to set EU, national and regional targets for P application rates. Here, we present a framework to evaluate current P management in European Union 27 Member States (EU27) agricultural land based on actual soil P concentrations, assumptions on optimal soil P concentrations, and modelled P uptake while giving guidelines for further improvement of national fertilizer recommendation systems to optimise P use in agriculture. The framework allows calculating the spatially explicit P input reductions required to meet soil health targets by 2050 and evaluates whether these reductions align with the 20 % decrease in P inputs proposed by EU policies targeting agricultural nutrient management practices.

2. Methods

2.1. Concepts and methodological approach

Sustainable P management follows the agronomic "Build-up, Maintenance or Mining" strategy when P inputs are more than, equal to, or less than crop P removal, respectively (Delgado et al., 2016; Sattari et al., 2012) and the soil P content is brought to a level needed for optimal crop yield. The soil P balance (SPB) (Amery et al., 2021) reflects which P management strategy is applied, calculated as the difference between P inputs (sum of organic and mineral fertilizers) and crop P removal (Amery et al., 2021). Ideally, the P management strategy should be based on the actual topsoil P status: a positive SPB should be adopted when P status is low (*i.e.,* build-up, more P is added than removed by the crop), negative when P status is high (*i.e.,* mining, less P is added than removed by the crop), and around zero when P status is optimal (*i.e.,* maintenance, the P input equals the crop removal) (Fig. 1). A previous study has suggested that a slightly positive SPB is necessary to maintain soil P levels, given the potential movement of available P to less available P pools and P losses due to erosion and subsurface flows (Amery et al., 2021). They proposed therefore a SPB between 1 and 10 kg ha^{-1}

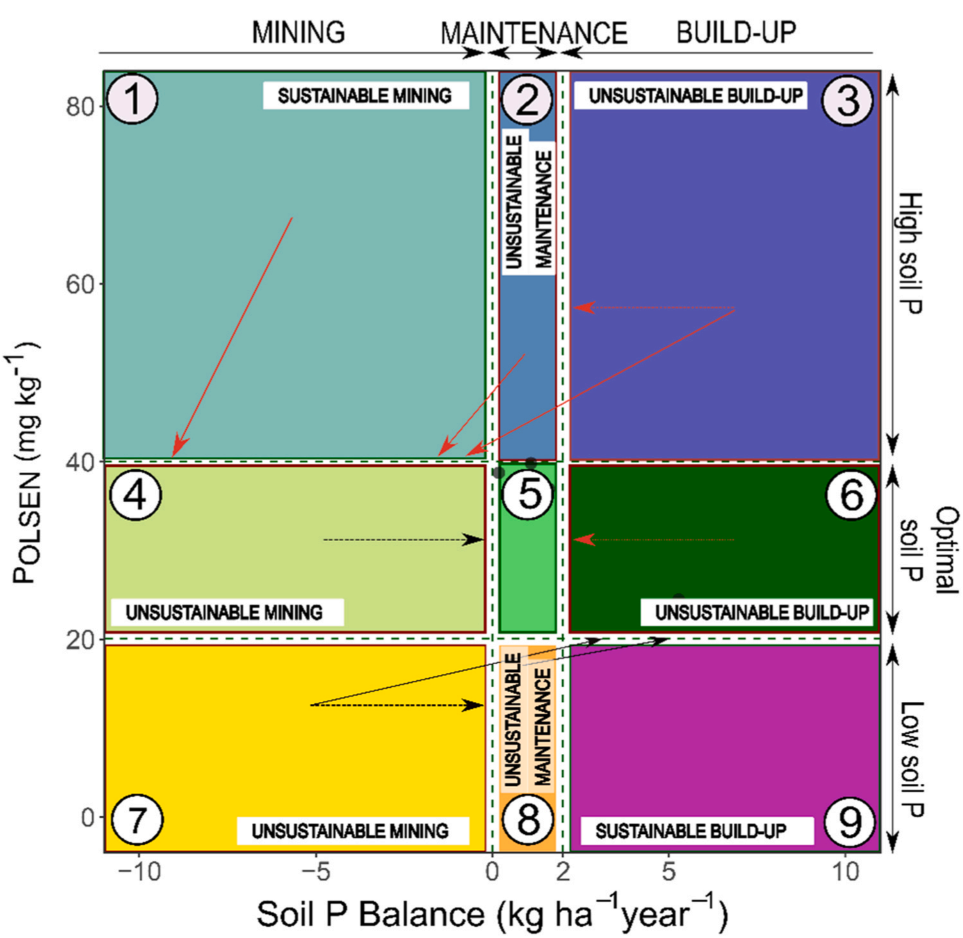

Fig. 1. The P management strategy can be divided into mining, maintenance or build-up strategy depending on the soil P balance (SPB: P inputs minus crop removal), as shown on the x-axis. Ideally, the P management strategy should be based on soil P levels (y-axis). If not, there is scope to reduce (red arrows) or increase (black arrows) P inputs. Dashed arrows show the movement to maintenance strategy (seen as a minimal effort), while the solid arrows show calculations when the aim is to increase or reduce soil P content (see Section 2.3 for calculations). We differentiated between 9 fertilization strategies, as shown by the numbers for each of the colored rectangles, depending on the soil P_{OLSEN} concentrations and SPB.

year^{-1} to maintain available soil P status. In our approach, we defined a SPB between 0 and 2 kg ha^{-1} year^{-1} as maintenance strategy, given that 10 kg ha^{-1} year^{-1} can be considered high in the EU for unavoidable P losses and the P inputs originating from deposition. This range of 0 – 2 kg ha^{-1} year^{-1} also accommodates estimated net P loss through erosion, estimated to be between 0.1 and 0.4 kg ha^{-1} year^{-1} (Alewell et al., 2020) or less than 0.5 kg ha^{-1} year^{-1} in EU agricultural soils (Panagos et al., 2022).

The soil P status is often assessed by a soil P test and established threshold values. There are at least 10 different methodologies used in the EU to assess soil P status in agricultural soils for fertilizer recommendations (Higgins et al., 2022; Jordan-Meille et al., 2012). All these methods are used as an indicator of the extent of available P in soils, and differ in their chemistry and the amount of P extracted (Nawara et al., 2017). A soil extraction with sodium bicarbonate (P_{OLSEN}) (ISO, 2021; Olsen et al., 1954) or ammonium lactate (Egnér et al., 1960) are most commonly used in the EU (Higgins et al., 2022). The P_{OLSEN} method is currently implemented in the soil monitoring framework across the EU (European Commission, 2023; Tóth et al., 2014), in the development of the EU soil degradation dashboard (Panagos et al., 2024) and the proposed EU directive on soil monitoring and resilience (European Commission, 2023). We will therefore use P_{OLSEN} in our approach (See Section 2.2), acknowledging that this method may not always give the best results among all methods for measuring available soil P and to identify environmental risks (Nawara et al., 2017; van Doorn et al., 2024).

To evaluate the current SPB in view of the soil P status, thresholds need to be defined to evaluate whether P_{OLSEN} concentrations are low, optimal or high. Thresholds to classify P_{OLSEN} concentrations vary widely across Member States and studies (Jordan-Meille et al., 2012; Nawara et al., 2017; Steinfurth et al., 2022) but are largely derived from long-term fertilizer trials where the crop yield response to P fertilization has been assessed. Steinfurth et al. (2022) compared the occurring P threshold concentrations across a selection of Member States, with conversion from the commonly used soil P test to P_{OLSEN} if necessary. The authors compared thresholds as the value above which P_{OLSEN} concentrations are sufficient, and the maintenance strategy should be applied. The threshold values proposed for optimum soil P status within the fertilizer recommendation systems ranged between 10 and 33 mg kg^{-1} for most countries, with some Member States (Belgium – Flanders and France) having threshold values between 50 and 60 mg kg^{-1}. In line with target P-Olsen ranges of most Member States as reported by Jordan-Meille et al. (2012), the European Commission proposed as threshold for soil P_{OLSEN} concentrations a value between 30 and 50 mg kg^{-1}, above which soils are considered unhealthy as they form a risk for environmental P losses and negative impacts on soil functioning (European Commission, 2023). Based on the mean optimum P_{OLSEN} value as being used in fertilizer recommendation systems across the Member States, we defined in our approach P_{OLSEN} concentrations below 20 mg kg^{-1} as low, between 20 and 40 mg kg^{-1} as optimal, and above 40 mg kg^{-1} as high (Fig. 1). In addition, we tested the impact of increasing or decreasing the lower and upper limit on the scope of reducing P inputs in the EU. Note that these threshold values might vary per crop (Nawara et al., 2017; Steinfurth et al., 2022), and soil P retention capacities (van Doorn et al., 2024). We used here the aforementioned fixed threshold values to illustrate the potential of this framework to guide the optimum P management strategies across Europe, with the potential for future improvement by crop- and soil-specific optimisation.

The current P management was divided into nine possible strategies based on the SPB and soil P concentrations, as shown by numbered rectangles in Fig. 1:

1. Sustainable mining with high soil P: P_{OLSEN} concentrations are above 40 mg kg^{-1} and SPB is negative, mining of soil P takes place in line with the high soil P concentrations. This is considered sustainable mining practice, as long as P_{OLSEN} remains greater than the threshold.
2. Unsustainable maintenance with high soil P: P_{OLSEN} concentrations are above 40 mg kg^{-1} and SPB is between 0 and 2 kg ha^{-1} year^{-1}. The latter may be viewed as unsustainable maintenance, P inputs should be reduced to decrease the high soil P concentrations and risk of soil P losses.
3. Unsustainable build-up with high soil P: P_{OLSEN} concentrations are above 40 mg kg^{-1} and SPB is above 2 kg ha^{-1} year^{-1}, which leads to unsustainable build-up of soil P. The P inputs should be reduced to reach at least a maintenance strategy (horizontal arrow), up to the level that soil P is mined, and soil P concentrations decrease (slanted arrow) to reduce the risk of soil P losses.

Following the same reasoning, when P_{OLSEN} concentrations are optimal, a maintenance strategy should be applied to keep optimal soil P levels:

4. Unsustainable mining with optimal soil P: When P_{OLSEN} concentrations are considered optimal, *i.e.,* between 20 and 40 mg kg^{-1}, and SPB is negative, unsustainable mining of soil P occurs. This may become unsustainable, especially in the lower range of P values, where P_{OLSEN} may reach values lower than 20 mg kg^{-1}. The P inputs could be increased to maintain the optimal soil P concentrations.
5. Sustainable maintenance with optimal soil P: When P_{OLSEN} concentrations are considered optimal, *i.e.,* between 20 and 40 mg kg^{-1}, and SPB is between 0 and 2 kg ha^{-1} year^{-1}, the optimal soil P concentrations are maintained.
6. Unsustainable build-up with optimal soil P: When P_{OLSEN} concentrations are considered optimal, *i.e.,* between 20 and 40 mg kg^{-1}, and SPB is above 2 kg ha^{-1} year^{-1}, unsustainable build-up of soil P occurs. P inputs should be reduced to reach a maintenance strategy (horizontal arrow).

Lastly, when P_{OLSEN} concentrations are low, at least a maintenance strategy should be applied with possible build-up to reach higher optimal soil P levels:

7. Unsustainable mining with low soil P: P_{OLSEN} concentrations are considered low, *i.e.* below 20 mg kg^{-1} and SPB is negative, which results in unsustainable mining. The P inputs should be increased when biomass production is hampered, at least to reach maintenance (horizontal arrow) or even to increase soil P concentrations (slanted arrow) to reach higher (optimal) soil P levels.
8. Unsustainable maintenance with low soil P: P_{OLSEN} concentrations are considered low, *i.e.* below 20 mg kg^{-1} and SPB is between 0 and 2 kg ha^{-1} year^{-1}, which may be considered unsustainable maintenance. The P inputs may be increased to reach higher (optimal) soil P levels.
9. Sustainable build-up with low soil P: P_{OLSEN} concentrations are considered low, *i.e.* below 20 mg kg^{-1} and SPB is above 2 kg ha^{-1} year^{-1}. This build-up strategy may be considered in line with the low P concentrations, when the aim is to reach more optimal soil P concentrations (Delgado et al., 2016).

By using the approach presented in Fig. 1, we evaluated the current P agricultural management in the EU27 based on the actual soil P concentrations (reference year: 2009). In addition, we calculated the amount of P inputs to be reduced or increased to reach optimal soil P concentrations in 41 years (period 2009–2050).

2.2. Data

We calculated the spatially explicit SPB as the P inputs (organic and mineral) minus the P removal by crops using the data from Muntwyler et al. (2024). Muntwyler et al. (2024) applied the DayCent model (Parton et al., 1998) to quantify P flows in EU agricultural land (*i.e.* cropland and grassland) at a spatial resolution of one km^2, incorporating the same data-derived soil properties as in this study, state-of-the-art input datasets, and representative management practices. The decade average national P mineral fertilizer consumption was spatially distributed following the crop specific differences in the theoretical agronomical requirement for 18 simulated arable and fodder crops. The mineral fertilizers were preferentially allocated to arable land. The input of organic P fertilizers (*i.e.* manure) was calculated based on the Gridded Livestock of the World map from FAO (Robinson et al., 2007) and P excretion rates for livestock categories (Muntwyler et al., 2024; Panagos et al., 2022).

The spatial distribution of topsoil P_{OLSEN} and P_{TOTAL} concentrations were retrieved from Ballabio et al. (2019) and Panagos et al. (2022). Both maps were created based on the data from the 'Land Use and Coverage Area frame Survey' (LUCAS) soil survey implemented in 2009 (Orgiazzi et al., 2018). The P_{OLSEN} concentrations were measured based on a soil extract with sodium bicarbonate (ISO, 2021) while P_{TOTAL} was measured after soil digestion with aqua regia (ISO, 1995). The limit of quantification of P_{OLSEN} in the LUCAS 2009 survey was 10 mg kg^{-1}. Concentrations below this threshold were set to this limit of quantification. We acknowledge that this adjustment is a source of uncertainty and might result in an underestimation of the required P inputs to increase soil P levels (see Section 2.3). Finally, the spatial data of soil bulk density based on the same LUCAS survey was used (Ballabio et al., 2016), to calculate P stocks (see Section 2.3).

2.3. Data processing

All the calculations were done for each one km^2 grid cell separately (Ballabio et al., 2016, 2019; Muntwyler et al., 2024; Panagos et al., 2022).

For each of the nine P management strategies (Fig. 1), we first calculated how much of EU agricultural land falls into the different combinations, and how much we can reduce P inputs based on the appropriate strategy to reach optimal soil P_{OLSEN} concentrations. The latter was not done for Strategies 5 and 9, as these are considered sustainable practices. For strategies 3 and 6 (unsustainable build-up with high or optimum soil P concentrations), we first calculated how much the P inputs can be reduced by moving from build-up to maintenance approach (horizontal arrows in Fig. 1). To do so, P required inputs were calculated (Eq. 1) and used to calculate the possible reduction in P inputs (Eq. 2):

$$P_{in,required} = P_{removal} + 2 \tag{1}$$

$$P_{reduction} = P_{in,actual} - P_{in,required} \tag{2}$$

with $P_{removal}$ the P removal by crop harvest and residue removal, and $P_{IN,actual}$ the actual P inputs, all in kg ha^{-1} $year^{-1}$ (Muntwyler et al., 2024). For strategies 4 and 7 (unsustainable mining with optimal or low P concentrations), a similar approach was used only that the required P inputs were set equal to the P removal by crops (*i.e.* SPB of 0 kg ha^{-1} $year^{-1}$). In that way, the minimal increase and reduction was calculated for these agricultural areas to reach maintenance strategy instead of mining or build-up.

In a second step, the required inputs were calculated to reach optimal soil P concentrations between 20 and 40 mg kg^{-1} P_{OLSEN}. We took a timeframe of 41 years, given that the soil data originate from 2009 and that the EU policy ambition is to have all soils healthy by 2050 (European Commission, 2021). To do this calculation, we had to estimate how soil P_{OLSEN} concentrations change when increasing or reducing P inputs for 41 years. Added P may not result in similar increase in P_{OLSEN}, as added soil P may be transferred to less available soil P pools while reduced P application may lead to increased P availability from less available P pools (Amery et al., 2021; Gu et al., 2023). We used the ratio of P_{TOTAL} over P_{OLSEN} as a simple proxy to account for these fluxes, as shown in Eq. 3:

$$P_{in,required} = P_{export} + \left[\left(P_{OLSEN,target} - P_{OLSEN,current} \right) * 0.2 * BD * \left(P_{total} / P_{Olsen,current} \right) \right] * 10 / years \tag{3}$$

where $P_{in,\ required}$ and P_{export} are P inputs and export in kg ha^{-1} $year^{-1}$, $P_{OLSEN,target}$ is the target P concentrations (20 or 40 mg kg^{-1} as shown in Fig. 1), and $P_{OLSEN,current}$ is the current P concentration (Ballabio et al., 2019), each expressed in kg kg^{-1}, BD the bulk density based on the spatial data in g cm^{-3} (Ballabio et al., 2016), multiplied with 0.2 m as soil sampling depth (Orgiazzi et al., 2018) and a unit correction (* 10) to convert to kg ha^{-1}. To correct for P entering less plant available P fractions not measured by P_{OLSEN}, the P input was subsequently multiplied by the ratio of P_{TOTAL} (measured by aqua regia) over P_{OLSEN}. Next, a division was conducted by the number of years (n = 41) based on the desired time to move from the current soil P status to the desired status in 2050.

The necessary reduction or increase in P inputs was subsequently calculated as shown in Eq. 2. For each of the nine P management strategies (Fig. 1), the total required change in P inputs in absolute terms (kg $year^{-1}$) was calculated by multiplying each cell value by 100 ha km^{-2}, given the spatial resolution of one km^2, followed by taking the sum of all relevant cells. In addition, we calculated the average current and required application rates for each of the nine P management strategies except for 5 and 9 (Fig. 1).To compare the necessary reduction in P inputs with actual inputs, the total P inputs, the total mineral P inputs and the total organic P inputs were calculated by summing the pixel values taken from Muntwyler et al. (2024) for all agricultural land.

To test the impact of the chosen optimal P range, the same calculations were done when changing both lower and upper limits (10 – 30 until 30 – 50 mg kg^{-1}), the lower limit only (10 – 40 and 15 – 40 mg kg^{-1}) and the upper limit only (20 – 25 until 20 – 60 mg kg^{-1}).

3. Results

3.1. Current P management strategies

When considering 20 – 40 mg kg^{-1} as optimal P_{OLSEN} concentrations, 33 % of EU27 agricultural land has high P concentrations, 50 % has optimal P concentrations, while 17 % has low P concentrations. These numbers confirm previous suggestions that EU27 is mainly characterized by optimal and high soil P stocks due to historical fertilization (Sattari et al., 2012; van Dijk et al., 2016). The spatial distribution of current P management strategies is shown in Fig. 2. Overall, most agricultural land in the EU27 is characterized by unsustainable maintenance with low P but there is large spatial variation and differences between and within countries (Fig. 2 and Table S1). Due to the relatively high P_{OLSEN} concentrations in Northern and Central EU, the P-management strategies applied are predominantly unsustainable build-up or sustainable mining. Moving more South, the P-management is characterized by sustainable build-up or unsustainable mining. Eastern European countries are either characterized by unsustainable build up with optimal or high soil P concentrations, or unsustainable maintenance or mining with low soil P.

3.2. Reducing P inputs in soils with high P levels

Phosphorus inputs must be reduced by 99 kilotons $year^{-1}$ to reach at least a maintenance instead of build-up strategy in soils with high or optimal soil P levels across the EU (Strategies 3 and 6 in Fig. 1). This accounts for 5 % of the current total P inputs (being 1841 kilotons $year^{-1}$), or 11 % of all mineral P fertilizers (being 938 kilotons $year^{-1}$) following the reported P inputs by Muntwyler et al. (2024). The P inputs can be reduced even more when a negative SPB is applied in agricultural areas with high soil P levels. When using this management strategy, soil residual P is expected to maintain crop production (Sattari et al., 2012), resulting in a decrease in soil P concentrations to reach 40 mg kg^{-1} after

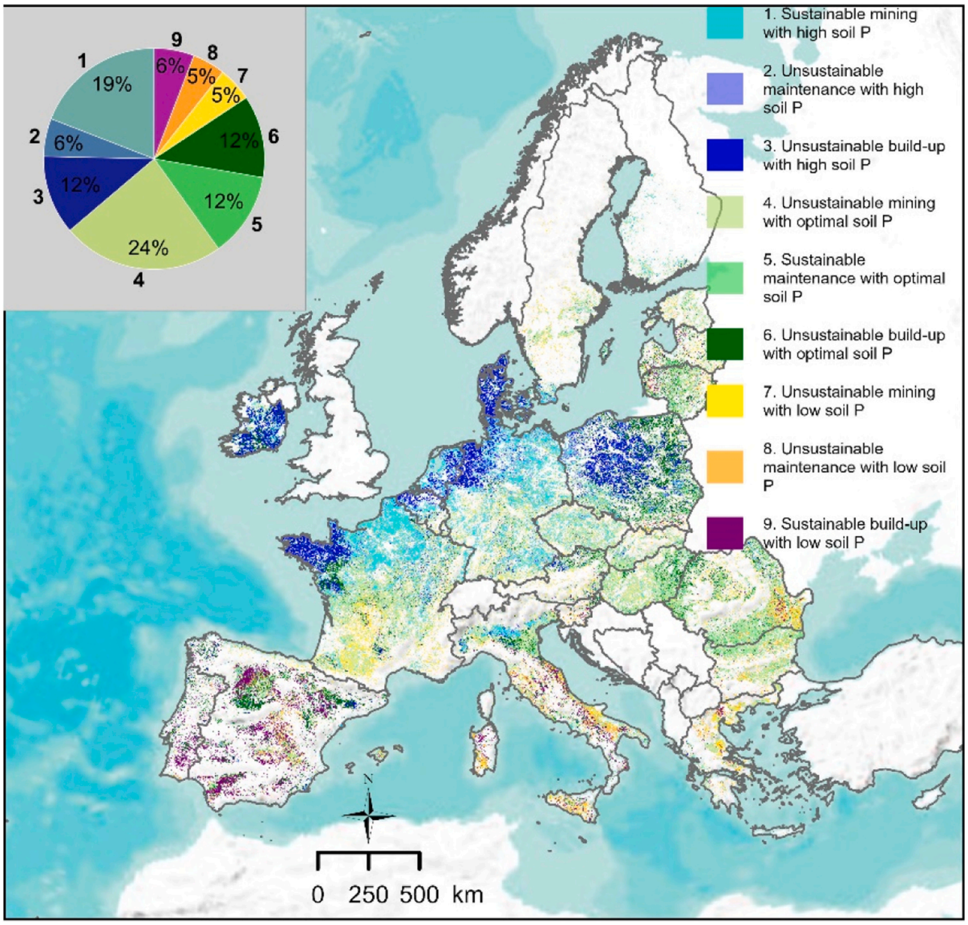

Fig. 2. The distribution of P management strategies in EU agricultural land. The different strategies are labeled by the same numbers as used to refer to the different strategies shown in Fig. 1. The pie plot in the left upper corner shows the % of EU agricultural land that falls into each of the nine categories shown in the map.

41 years (solid arrows in Fig. 1 for strategy 3). In regions with high soil P levels where there is currently unsustainable build-up (Denmark, Ireland, the Netherlands, Flanders and Brittany, Northern Germany), P inputs can be reduced by additional 189 kilotons year^{-1} until 2050 (diagonal arrow for strategy 3 in Fig. 1). P application rates need to be reduced on average by 14 kg ha^{-1} year^{-1} in these areas (Table S2). Even in those regions where the high soil P concentrations are currently mined (Strategy 1 in Fig. 1), P inputs can be further reduced with 103 kilotons year^{-1} or 4 kg ha^{-1} year^{-1} on average, resulting in a more negative SPB to reach soil P levels of 40 mg kg^{-1} in 41 years. For some agricultural areas where currently soil P is mined, the threshold of 40 mg kg^{-1} will be reached before 2050, and these areas were not considered for the calculations. It must be noted that for some agricultural areas where high soil P is currently mined, maintained or built-up, applying zero P inputs would not reduce P concentrations below 40 mg kg^{-1} in 41 years. This applies for agricultural areas in North of France, Flanders, the Netherlands, North of Germany and South of Sweden (Fig. 3b and Figure S1).

The sum of the reductions in P inputs equals 384 kilotons per year, which accounts for 21 % of total P inputs, or 41 % of the total mineral P inputs currently applied in EU27 agricultural land. The spatial distribution of the necessary reduction in P inputs to reach optimal P concentrations after 41 years, is shown in Fig. 3c. When aiming to reduce P levels at least to 40 mg kg^{-1} by 2050, P inputs need to be reduced mostly in Belgium, Netherlands, Denmark, and Ireland (Table S1). In France, the average required reduction in P inputs to reach optimal soil P concentrations in 41 years is less than aforementioned countries (Table S1). However, there is large variation in required P input reductions within the country, pointing towards the importance of regional P input targets especially in Northern regions of France (Fig. 3c) next to field-tailored recommendations.

3.3. *Increasing P inputs in soils with low P concentrations*

In some regions where P concentrations are below 20 mg kg^{-1} or between 20 and 40 mg kg^{-1}, P mining is occurring. This further decrease in soil P concentrations may hamper biomass production. When in these regions at least a maintenance P management strategy is applied (vertical dashed arrows for strategies 4 and 7 in Fig. 1), P inputs need to be increased by 103 kilotons per year. Considering the reduction in P inputs discussed in the previous section, this would mean a total reduction of P inputs of 281 kilotons per year in the EU, which equals 15 % of total P inputs or 30 % of mineral P inputs. For most of the areas, the increase in P inputs is between 0 and 10 kg ha^{-1} year^{-1} and located in Southern France, Greece, Czech Republic, and Hungary (Fig. 4).

If at least 20 mg kg^{-1} of P_{OLSEN} concentrations is aimed to be reached in these regions (diagonal dashed arrows for strategies 4 and 7 in Fig. 1), P inputs need to be increased by 263 kilotons per year in the EU. The total reduction of P inputs in EU27 is then 122 kilotons of P inputs year^{-1}, which is 7 % or 13 % of total and mineral P inputs respectively.

The choice of threshold values has consequences for the calculated scope of input reductions, as shown in Fig. 5. Increasing the upper limit equal to or above 45 mg kg^{-1} would mean a net increase in P inputs, while reducing the lower and both lower and upper limits would result in a further potential decrease in P inputs.

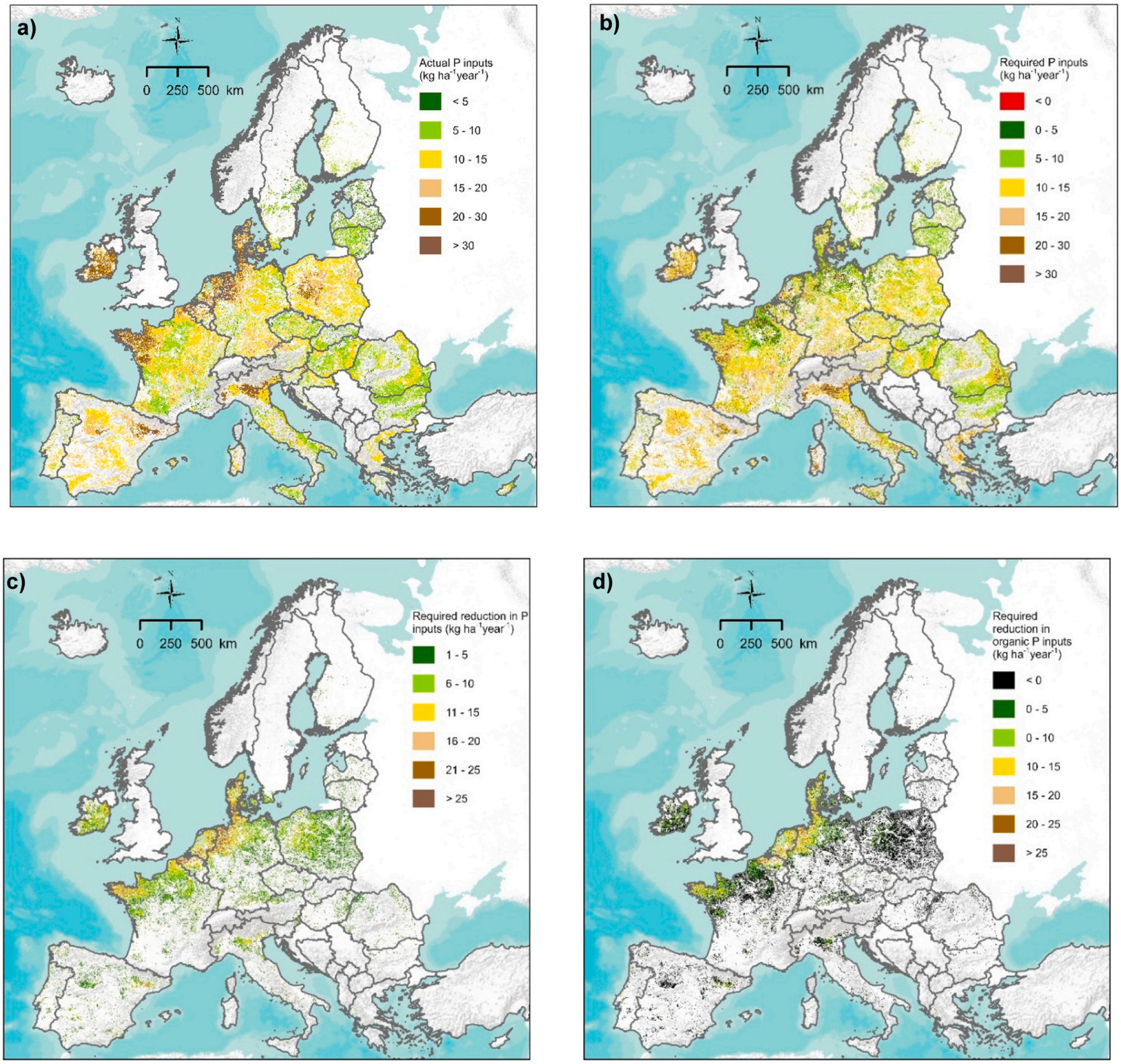

Fig. 3. (a) Actual inputs (kg ha^{-1} year^{-1}) taken from Muntwyler et al. (2024); (b) required P inputs (kg ha^{-1} year^{-1}) according to our calculations. The regions in red in Fig. b are those regions with high P_{OLSEN} concentrations, where according to our calculations, after 41 years with zero P inputs the P_{OLSEN} concentrations will still be higher than 40 mg kg^{-1}; c) The reduction in P inputs needed to have the sustainable management practice in line with soil P concentrations and to reach optimal P concentrations in 41 years (solid arrows in Fig. 1); d) The reduction of current organic P inputs needed to reach optimal P concentrations in 41 years. When zero reduction in P inputs are needed, it means that all the input reduction shown in Fig. 4a can be covered by reducing mineral P inputs.

4. Discussion

4.1. Variation in optimal values of P_{OLSEN}

Comparison between P_{OLSEN} threshold concentrations to apply maintenance strategy, showed a large variety among EU Member States, with differences up to 40 mg kg^{-1} (Jordan-Meille et al., 2012; Steinfurth et al., 2022). Lowest threshold values were found in Italy, Spain, Poland, and Wallonia (10 – 17 mg kg^{-1}), while highest concentrations were found in Flanders and France (55 – 59 mg kg^{-1}). The optimal range applied in this study (20 – 40 mg kg^{-1} for P_{OLSEN}), can be seen as a compromise between these two extreme cases currently applied in Member States based on evaluation of field trials.

Setting a threshold value to define proper P fertilization is challenging (Bai et al., 2013; Nawara et al., 2017). First, threshold values for P_{OLSEN} can vary between crops: critical P concentrations above which crop species did not respond to P fertilization, were found to vary between 10 and 18 mg kg^{-1} for wheat and between 19 and 76 mg kg^{-1} for potato (Nawara et al., 2017). This is largely due to differences between crops' efficiency to take up P from topsoil and subsoil as well as from less available P pools (Hinsinger, 2001).

Second, threshold values may also vary between soil types as long as the soil P test is not correcting for this: *e.g.* P_{OLSEN} threshold values ranged between 8 and 46 mg kg^{-1} depending on the location of the field trials across Europe (Nawara et al., 2017), which can be explained partly by differences in P biogeochemistry (Beegle, 2015).

Next, due to hysteresis of P adsorption and occlusion, relatively older P may become less available, leading to higher threshold values (Smolders et al., 2021).

Lastly, discrepancies between existing soil P threshold levels among

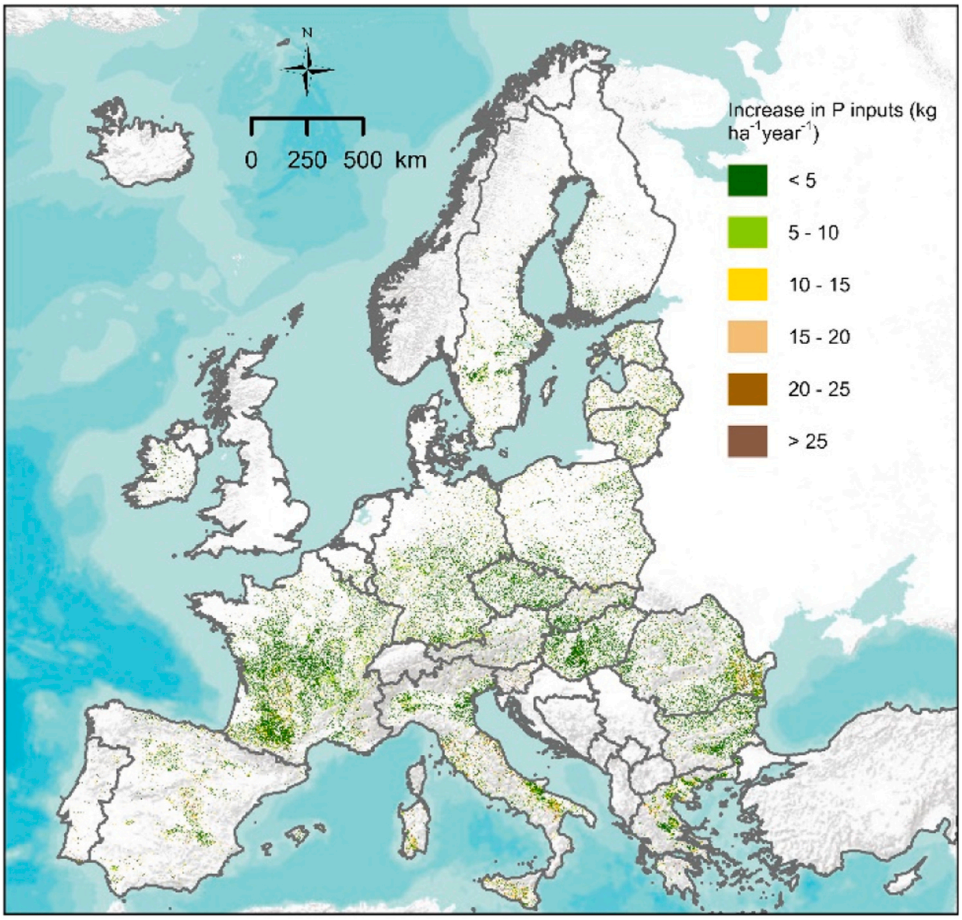

Fig. 4. The increase in P inputs required when the aim is to reach at least 20 mg kg^{-1} of topsoil P_{OLSEN} concentrations by 2050.

Member States may be partly explained in how these threshold values have been established. Agronomic data used to establish threshold values often contain a lot of unexplained variation. The associated uncertainty about the resulting threshold values can be solved by using 'high enough' threshold values to minimize the risk of compromising yields (Steinfurth et al., 2022). Steinfurth et al. (2022) raised the question whether for example Flanders has applied a strong yield security approach, resulting in relatively high threshold values around 60 mg kg^{-1} of P_{OLSEN} compared to other Member States. In addition, Member States show variation in the selected crop(s) to determine the optimum soil P threshold value (e.g., France, the Netherlands), and acceptable yield loss (e.g., 1 %, 5 % or 10 %). Given the expected increase in yield fluctuations due to climate change in the European Union (Schmidt and Felsche, 2024), a critical discussion around soil P threshold levels and yield security, as well as the effect of negative SPB on yields, can be helpful to design future policies. Further harmonization and transformation using the P saturation degree with the oxalate extraction, can be a feasible approach allowing countries to adjust their fertilizer recommendation systems while building upon existing agronomic knowledge bases currently used (van Doorn et al., 2023, 2025).

One might question the use of single threshold values for the optimum soil P status guiding P fertilizer use, in particular since the crop yield response to the availability of P is also affected by the availability of other factors (Lemaire et al., 2021), thereby contradicting the underlying concepts of the law of the minimum.

Note that in most arable farming systems crops are grown in rotation. Therefore, it makes sense to include a range of optimal values over the crops being present. In addition, spatial variation in P_{OLSEN} within the one km^2 cropland area can be large as shown by the high resolution maps for comparable P pools in the Netherlands (van Doorn et al., 2024) though eventual under- or overestimations cancel out when applied on the coarser resolution of one km^2 as done in our analysis.

We have used optimum P-Olsen concentrations between 20 and 40 mg kg^{-1} to guide and evaluate the current P management practices across the EU and to calculate the P input reductions to reach optimal soil P levels. The results can be viewed as the "minimum effort" value, as we used 20 and 40 mg kg^{-1} as target concentrations for regions with low and high actual P levels, respectively. However, we have shown that the calculations are sensitive to the choice of threshold values. When changing the optimal range from 20 to 40 mg kg^{-1} to 20–30 mg kg^{-1}, the share of soils with high P concentrations goes from 33 % to 57 % of total agricultural area. In addition, the scope for reducing P inputs increases with more than a factor two (Fig. 5). When increasing the upper limit to 50 mg kg^{-1} instead of 40, the share of soils with high P concentrations goes from 33 % to 12 %, and we calculated a net increase in P inputs in EU27 (Fig. 5).

It must be noted that differentiation between soil and crop types was not done in our analysis, as the same threshold values were applied across the EU and we focused on the optimization of P management strategies across European regions. Nevertheless, a relatively large range of 20 – 40 mg kg^{-1} was chosen for the optimal P_{OLSEN} concentration, being a compromise of the threshold values found in studies compiling field experiments across the EU (Nawara et al., 2017; Steinfurth et al., 2022) and current thresholds used by Member States for fertilizer recommendations.

The optimum P_{OLSEN} threshold used in this study is an agronomic target value to maximize crop yield in view of the primary production of the European agroecosystems. This optimum value however might exceed the critical P_{OLSEN} threshold required to reduce the P load to surface water in some agricultural fields, a necessity to reach the desired

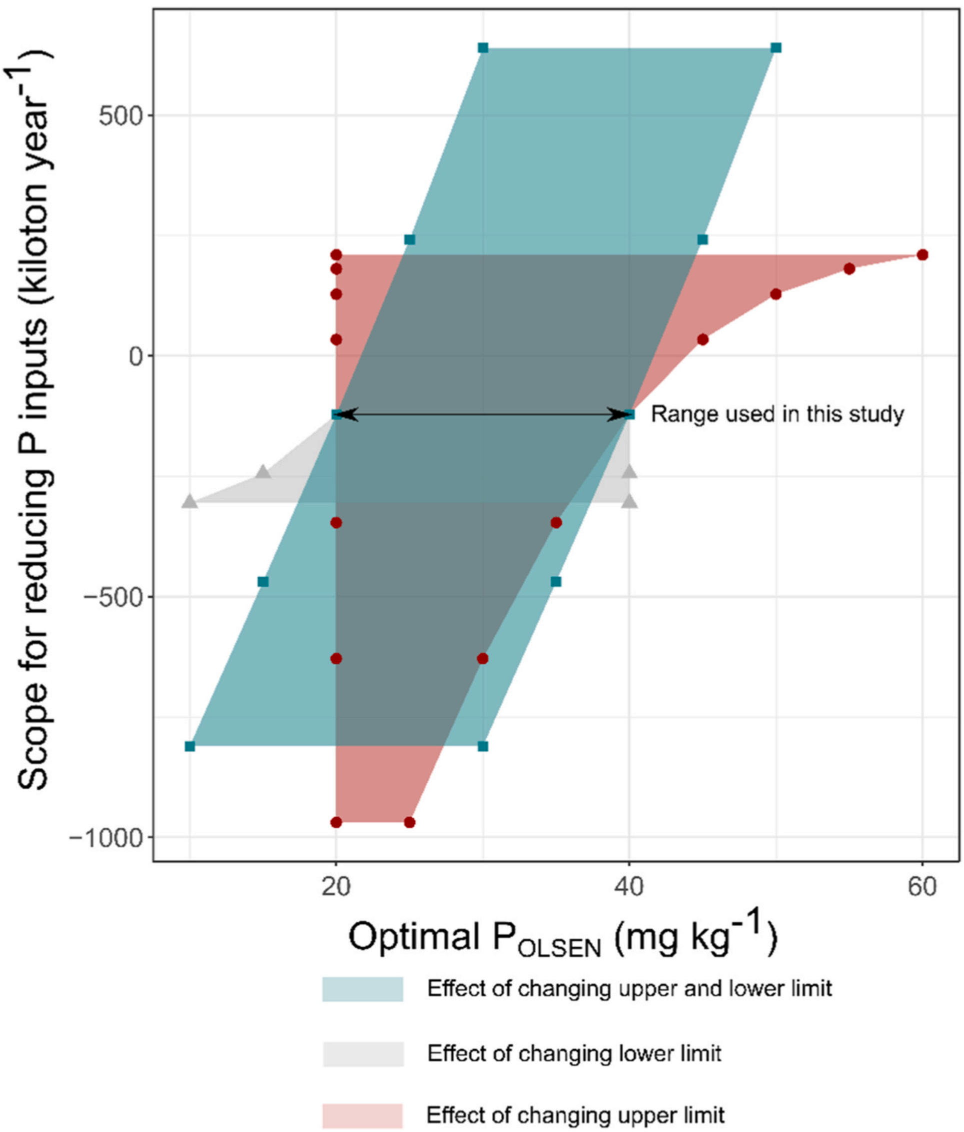

Fig. 5. The calculated scope for reducing P inputs when changing the optimal P_{OLSEN} range. The horizontal ranges of the colored areas show the range in optimal P_{OLSEN} (x-axis) used to calculate the scope for reducing P inputs (y-axis). The arrow shows the range applied in the main text of this manuscript (20 – 40 mg kg^{-1} with the scope to reduce P inputs by 122 kilotons per year). Compared to the range applied in the main text, the blue area shows the effect on the scope for reducing P inputs when increasing or decreasing both the lower and upper limits, the grey area shows the effect when decreasing the lower limit, and the red area shows the effect when increasing or decreasing the upper limit.

aquatic biodiversity in rivers and also the marine environment (van Doorn et al., 2025). Whether the critical environmental P_{OLSEN} threshold exceeds the agronomic target might vary depending on soil type and geomorphological properties of the fields and surrounding landscapes. Embedding an environmental critical threshold in the Build-Up and Maintenance Strategy implies a shift in how soil P is currently measured in routine agronomic soil testing for designing properly the land management practices (i.e., soil, crop, water, and fertilizer practices as well erosion control practices) to reconcile agronomic and environmental objectives.

Our results also highlight the long time needed to reduce soil P concentrations by nutrient management. We even identified areas where the target of 40 mg kg^{-1} P_{OLSEN} concentrations will not be reached after 41 years of zero P application. These results highlight the importance of agricultural practices that control erosion and runoff in addition to crop, soil and nutrient management practices increasing the P use efficiency (de Vries et al., 2023), in order to reach the water quality objectives as outlined in the Water Framework Directive (European Commission, 2000).

4.2. *The fate of P surplus*

The accumulation of P inputs in soil and its availability for crop uptake is largely controlled by the P retention capacity. We assumed that soils with higher P retention capacity, will need more P inputs compared to P removal by crops in order to increase soil P_{OLSEN} concentration with the same amount (McDowell et al., 2024; Sattari et al., 2012). Similarly, soils with low P retention capacity need less P inputs compared to P removal to decrease soil P_{OLSEN} concentrations due to diffusion and desorption from more stable to more available pools. We approximated both effects by using the ratio of P_{TOTAL} over P_{OLSEN} as a proxy to calculate how much inputs are required to lower or increase soil P_{OLSEN} concentrations.

Some studies refer to the inverse ratio as the phosphorus activation coefficient (Sharma and Chowdhury, 2021; Q. Wang et al., 2022; Wu et al., 2017; Yang et al., 2019; Zhan et al., 2015). Zhan et al. (2015) found that increase in soil P status was positively correlated with the phosphorus activation coefficient, strengthening the use of the inverse ratio in our approach. Across EU27 the ratio varied from 4 to 83 with a mean value of 20. These ratios show that the majority of the added P surplus ends up in a reactive P pool, likely the P sorbed to metal(hydr) oxides, potentially buffering the weakly bound P being measured with P_{OLSEN} (McKenna et al., 2024). Other field experiments, particularly those conducted in China, show that the percentage of P surplus ending up in the P_{OLSEN} pool might vary with a factor 10 or more (being on average 15 %), whereas the variability is much smaller when another reactive P pool as P-oxalate was used (Gu et al., 2023).

Since the spatial variation in aluminium-and iron (hydr)oxides across Europe has not been analysed in LUCAS topsoil database so far, we argue that the ratio of P_{TOTAL} over P_{OLSEN} is the best proxy for the moment to account for site specific retention of the added P. Note that we also assume that this ratio does not change over time, and that its effect on the replenishment of the pool of available P stays constant over the 41 years. However, this phenomenon may become slower over time after prolonged negative SPB due to hysteresis of P adsorption and occlusion processes (Smolders et al., 2021).

The replenishment of the available P by more stable P has been found to depend on other factors such as pH, metal(hydr)oxides, organic carbon and clay content (Wang et al., 2022). McDowell et al. (2024) used a so-called soil P retention class to account for all these factors in their calculations of the global P inputs needed to increase P_{OLSEN} to an optimal threshold of 15 mg kg^{-1} in one single year. They argued that to increase P_{OLSEN} with 1 mg kg^{-1}, application of 6, 8, 10 or 13 kg ha^{-1} is needed, depending on the soil P retention class. The latter was taken from a global map of the soil P retention capacity based on clay, pH, and CEC (Batjes, 2011).

Similarly, Sattari et al. (2012) calculated fertilizer requirements accounting for P diffusion, using constant fractions (20 % of labile P) moving to the stable pool every year, with 30–40 % of stable P moving to the labile fraction each year, depending on the continent. Since the distribution of P inputs over the plant available, weakly bound and strongly bound P pools is strongly controlled by the soil P retention capacity, our approach might better reflect the actual variation over space but might also lead to slightly over- or underestimations of the desired change in P inputs to reach the target levels for P_{OLSEN} by 2050. Given the strong spatial variability and the uncertainty in the P accumulation in P_{OLSEN}, the main principles of our framework remain valid. The proposed framework can still be improved by incorporating insights into the fraction of the total P pool that is reversibly bound and the capacity of soils to bind P, in order to complete the information provided by the P_{OLSEN} soil test (Magnone et al., 2019). Based on theoretical considerations as well as data driven illustrations for the Netherlands, van Doorn et al. (2023) showed that for instance the oxalate extraction method is a better alternative to underpin the nine fertilizer strategies as given here (Fig. 1), in combination with the P saturation degree based on measurements of aluminium and iron in the same extract.

4.3. Uncertainties in EU soil nutrient management: model, data, and future trends

The spatial variation in current and desired soil P status and associated P management options represent scenarios illustrating the potential for improvement in the current P management on regional level. Uncertainties and limitations persist, in particular on field but also on regional level, stemming from missing processes, (*e.g.* the unknown P retention in various EU soils, model assumptions such as the exclusion of manure trading) and input data, for example the estimates of P inputs and outputs at one km^2 resolution are often based on regional data sources (mineral fertilizers, crop shares) distributed based on specific criteria (Muntwyler et al., 2024). Also, the model's comprehensiveness could be enhanced by integrating overlooked P flows in the SPB (e.g., P erosion, deposition of sewage sludge and compost) as more suitable datasets become available, improving our understanding of regional disparities. The current framework presented in this study, may be further improved by the increased availability of spatial and temporal data on nutrients, expected under the regulation on statistics on agricultural input and output (European Parliament and the Council of the European Union, 2022), and the P sorption capacities of European soils.

We calculated scenarios for 2050, but uncertainties exist about which crops will be cultivated in the next 2–3 decades and their requirements and efficiencies in terms of P. In addition, our assessment of actual and desired P inputs can be further optimized when the optimum soil P threshold can be adjusted for new management approaches increasing the P use efficiency of the cropping system.

4.4. P regulating policies

Currently, there are no EU policies that directly limit the application of P to EU agricultural soils. The Nitrates Directive (European Union, 2008) indirectly limits P application by manure, due to the limit of N application from manure, which is 170 kg ha^{-1} $year^{-1}$. However, using estimates of N-P ratios in different manure types (see Table S3 in Supplementary Information), this limit on N application by the Nitrates directive is estimated to indirectly limit P application up to 27–70 kg ha^{-1} $year^{-1}$ depending on the type of manure (Vlaamse Landmaatschappij, 2024). These application rates are higher than the required P inputs we have calculated in this study to reach optimal P levels by 2050, especially in livestock dense regions such as Brittany (France), Flanders (Belgium), the Netherlands, Catalonia (Spain), Emilia Romagna (Italy), Denmark and Ireland (Fig. 3b). Some of these regions do have explicit P application limits. For example, Denmark has defined 921 crops and land covers with specific P application limits, mostly ranging between 15 and 30 kg ha^{-1} $year^{-1}$ (Danish Ministry of Food Agriculture and Fisheries, 2024). Flanders, the Netherlands and Ireland have specified limits also dependent on soil P concentrations and land use (Irish department of Agriculture Food and the Marine, 2024; Rijksdienst voor Ondernemend Nederland, 2019; Vlaamse Landmaatschappij, 2024). For soils with high P concentrations, Ireland has set the limit to zero P application per year, with exceptions for some crops such as potatoes. In Flanders and the Netherlands, maximal allowed application rates for soils with high P concentrations are between 20 and 30 kg ha^{-1} $year^{-1}$.

When maximal allowed application rates exist in national legislations, they are generally higher than required P inputs to reach optimal soil P concentrations by 2050 according to our calculations (Fig. 3b). Our calculations showed that for most agricultural land in these regions, between 0 and 20 kg ha^{-1} $year^{-1}$ is required. Depending on the type of manure, this P application would mean an N application of maximum 50–125 kg ha^{-1} $year^{-1}$ (Table S3). Our results show that limit values on manure application based on P requirements using the framework applied in this study, would result in lower N application limits than what is currently allowed in the Nitrates Directive (European Union, 2008). Imposing limits on manure application based on soil P would result in a possible shift towards more mineral N fertilization and may impose difficulties for organic farms to meet crop N requirements by external inputs or increasing the need of N-fixing crops in the rotation. Similarly, the carbon input will be lower since organic manure can contribute up to 50 % of the annual inputs compensating the natural carbon decomposition in soils. The separation and processing of manure, and the reuse of biowaste streams may therefore become increasingly important when future policies aim to meet both N and P crop and requirements and environmental objectives. In addition, the processing of manure in livestock dense regions can enhance transportation (Vaneeckhaute et al., 2013) in order to meet 56 % of the P demand in Southern EU regions where current soil P concentrations are low. The recently proposed Vision for Agriculture and Food stresses the issue of nutrient management from livestock, and promotes circularity from regions with high livestock density in order to reduce use of synthetic fertilizers (European Commission, 2025).

5. Conclusions and way forward

Although there is currently no direct EU policy targeting P application rates in agricultural soils directly, recent EU policy developments may have implications for P fertilization in the future. We have presented a framework to calculate spatially explicit opportunities for reducing P inputs in EU agricultural land. The results and the framework, possibly improved with more regional data and experiments, provide the necessary support for policy makers to set regional targets when it comes to P application rates and soil P concentrations.

In our framework, we have defined low, optimal and high soil P concentrations and made an assumption of the long-term fate of P inputs in soil. Using these assumptions, we calculate that there is the opportunity to decrease total P inputs by 21 % in EU27 agricultural area. The areas in which there is scope for reducing P inputs are mainly located in North of France, Flanders, Netherlands, Germany, Denmark, Poland and Ireland. Our study highlights that current and required P application rates vary greatly between and within EU Member States, urging the need for regional targets, policies and a reflection on nutrient transport across Member States.

CRediT authorship contribution statement

Panos Panagos: Writing – review & editing. **Arthur N. Fendrich:** Writing – review & editing. **Elise Van Eynde:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Felipe Yunta:** Writing – review & editing, Writing – original draft, Conceptualization. **Gerard H. Ros:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Philippe Hinsinger:** Writing – review & editing, Writing – original draft. **Anna Muntwyler:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104168.

Data availability

The data used for this publication is all available on EUROSTAT or ESDAC. No new data were generated.

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