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Assessing the phosphorus demand in European agricultural soils based on the Olsen method

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ABSTRACT

Overcoming the consequences of future scarcity of P is crucial to ensure agriculture sustainability. This requires decision-making processes depending on data on the P status of agricultural fields, commonly conducted with soil P tests (SPTs), and efficient use of the resource on a societal scale following a circular economy approach. All this will decrease the P losses and the subsequent environmental impact. However, SPTs are not universal and, even for a given SPT, the definition of threshold values for fertilizer response is not accurate. This work aimed to define models to predict Olsen P threshold values, allowing the identification of P-responsive sites at the European scale as a basis for more accurate and sustainable P fertilization schemes based on a circular economy approach. To this end, a data set was compiled based on a literature review that describes the Olsen P threshold values for different crops under field conditions. Subsequently, an analysis of potential P fertilizer requirements was performed on agricultural soils of the European Union (EU) using the data set of the LUCAS project and how this need can be covered with a circular economy approach.

Environmental factors were more relevant than crops to explain the variation in threshold values. A regression model involving soil pH and clay content and annual average rainfall as independent variables explained 61% of the variance in Olsen P threshold values. When soil pH and clay content were the only explanatory variables, the explained variance was 49%. This reveals the need to take into account factors related to P buffer and sorption capacity to estimate accurate threshold values. We detected that only 27.8% of EU cropland soils and 42.7% of grassland soils were P-responsive. We can conclude that a more precise allocation of the resource is possible in P-responsive sites and also that most of the European demand for P could be covered by recycling P from manure, wastewater, and municipal solid waste.

1. Introduction

There is a general consensus in the scientific community on the implications that phosphorus (P), as a finite and highly strategic resource, will have on future agricultural production and food security (Cordell et al., 2009; Keyzer, 2010; Van Vuuren et al., 2010; Cordell and White, 2014; Cordell and Neset, 2014; Helin and Weikard, 2019). This is a particularly relevant issue in Europe, where agricultural production depends on imported P (Ott and Rechberger, 2012; Schoumans et al., 2015; Van Dijk et al., 2016). However, P is inefficiently used in society, and particularly in the food chain. Phosphorus in human diet or animal feed is usually higher than needs, and only a fraction of P is digestible. In fact, 54% of total P losses occur from human consumption, mainly from sequestration of P in sewage sludge and organic waste (van Dijk et al., 2016). Relevant P losses can also occur in food processing, such as those of animal origin (e.g., bones). Thus, P in manure, food processing and urban waste and sewage sludge may account for a significant portion of P used in agriculture (around 80% according to van Dijk et al., 2016). On

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Abbreviations: SPT, Soil P test; GLM, General Linear Model; AIC, Akaike information criterion; RMSE, Root mean square error; MAE, Mean absolute error; LOOCV, Leave-one-out cross-validation.

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the other hand, there is an excessive accumulation of P in agricultural soils, the legacy P, resulting from inappropriate fertilization practices that usually leads to relevant environmental problems (Le Noë et al., 2018; Pavinato et al., 2020; Gatiboni et al., 2020). Thus, ensuring agricultural sustainability and consequently future food security requires more efficient use of the P resource at the societal scales, decreasing losses and increasing the environmental performance in its use (Schröder et al., 2011; Nesme and Withers, 2016; van Dijk et al., 2016). To this end, it is necessary: (i) more efficient P fertilization schemes involving a more accurate estimation of P requirements by crops, and (ii) circular economy approaches in the use of P that should take into account recycled sources of the nutrient.

Efficient P fertilization schemes should rely on a decision-making process involving: (i) data related to soil P status, usually chemical P extraction, the so-called soil P tests (SPT), (ii) interpretation of these data in relation to crop production, and (iii) fertilizer recommendations derived from this interpretation (Neyroud and Lischer, 2003; Delgado and Scalenghe, 2008; Jordan-Meille et al., 2012). Interpreting SPT in relation to crop production requires the definition of threshold values above which no yield increase is expected with P fertilization (Mallarino and Blackmer, 1992; Colomb et al., 2007; Jordan-Meille et al., 2012). This allows the focused application of the P resource to soils where the highest return of fertilization can be achieved, that is, sites responsive to P (Recena et al., 2016). Fertilization schemes recommend increasing P rates at decreasing SPT values (Tunney et al., 2003; Delgado and Scalenghe, 2008; Delgado et al., 2016). The target is to (i) increase the SPT values to a value around or above the threshold value and maintain it by replacing crop exports ("build-up and maintenance" strategy), or (ii) avoid P fertilization above the threshold values ("sufficiency strategy"). This latter option is intended to reduce the environmental risks ascribed to P loss and to improve the use of legacy P (Olson et al., 1987; Delgado et al., 2016; Le Noë et al., 2020). These schemes are essentially empirical, without a mechanistic basis, and are usually described in technical/grey literature more than in scientific literature (Jordan-Meille et al., 2012).

Although this decision-making process is common for P fertilizer recommendations in many regions of the world, the basis for its application, the SPT, is not universal. Many authors have described the reasons for the lack of universality of a given chemical extractant to be used as SPT (Delgado and Torrent, 1997; Delgado and Scalenghe, 2008; Jordan-Meille et al., 2012; Sánchez-Alcalá et al., 2015; Nawara et al., 2017). In summary, the ratio of P uptake to SPT values and the relationship between crop yield and SPT values vary depending on (i) soil properties affecting P dynamics and extractant performance, and (ii) dominant P forms. These reasons also hinder the estimation of the values of a given SPT based on other SPTs in soils that vary widely in their properties. As an example, in a European soil collection, Barberis et al. (1996) observed that the relationship between the Ca lactate method (Schuller, 1969) and Olsen P (Olsen et al., 1954) did not allow an accurate estimation of values of one method based on the other ($R^2 = 0.35$). In this soil set, the ratio of total available P in soil, determined by cumulative P extraction in successive crops until depletion of the available pool, to Olsen P decreased with increasing soil pH (Delgado and Torrent, 1997). In fact, this means that the threshold values will vary for the same SPT depending on the soil properties. In practice, many SPTs have been developed for specific geographic regions, and around 10 official tests have been described in Europe alone (Neyroud and Lischer, 2003; Jordan-Meille et al., 2012). However, even for a given SPT, the ratio of P uptake to SPT value and the threshold values for fertilizer response may vary within a region with relatively homogenous soil types (Sánchez-Alcalá et al., 2014; Recena et al., 2015, 2016; Tandy et al., 2021). Only methods based on near-infinite P sinks seem to provide more homogeneous ratios of P uptake by crops to extracted amounts (Delgado and Torrent, 1997; Tandy et al., 2011; Santner et al., 2015; Recena et al., 2017), but their practical performance in labs is more complex. Additionally, there is less information on the field scale on the threshold values for fertilizer response for such methods. Thus, a conjunction of factors, involving also tradition and legal aspects in fertilization (some extractions are official methods), slows progress in the definition of new accurate and easy-to-apply SPTs.

All this makes it difficult to define a picture on a continental scale, allowing the definition of a general scheme to assess the current status of P in the soil in relation to crop yields and fertilizer demand. Tóth et al. (2014) described the European Union situation based on Olsen P, perhaps the most common SPT used in scientific literature, using the LUCAS project dataset (https://esdac.jrc.ec.europa.eu/projects/lucas). However, this study did not consider that Olsen P fails to identify P-responsive sites for such a large collection of soil samples, as threshold values are affected by soil properties. This can be solved with an estimate of threshold values based on soil properties routinely determined in soil analysis, as proposed by Recena et al. (2016). However, these researchers made a proposal based on pot experiments and with a soil collection with a relatively limited range of properties (e.g., pH ranging from 6.5 to 8.3). To use this approach in the estimation of Olsen P threshold values on the European scale, evidence of its suitability is required in soils that vary widely in their properties. In addition, it is necessary to define the relationship between Olsen P and the yield based on field experiments under a wide range of climatic conditions and crops. We hypothesized that it is possible to accurately estimate the Olsen P threshold value using routinely determined soil properties, climatic conditions, and crop type. Since only a minor part of P in human diets or animal feed is really accumulated in consumers, it can also be hypothesized that there is room for a significant recovery of P from wastes to use this non-renewable resource more efficiently, thus decreasing losses and subsequent environmental impact. The objectives of this work were, on the basis of a literature review, (i) to define a simple model for the estimation of Olsen P threshold values that will allow the identification of P-responsive sites at the European scale, as a basis for a more accurate and sustainable decision-making process in P fertilization, and (ii) to assess the potential of P recycling to cover needs in agriculture at the European scale as a basis for a circular economy-based strategy in the management of the P resource.

2. Materials and methods

2.1. *Dataset*

The literature review was performed using scientific databases (Web of knowledge and Scopus, Science Direct, University of Minnesota, Rothamsted research, Wiley Online Library, CSIRO, Soil Science Society of America), Google scholar, and Google since the information may also be as technical/grey literature. To this end, the following keywords or their combinations were used: phosphorus, Olsen, threshold value, long-term fertilization, critical soil P, soil test, availability, crop yield, phosphorus status, long-term fertility, fertilizer recommendations, fertilizer use efficiency. The selection of the information was not limited to Europe to encompass a wide variability in crops and environmental conditions.

Articles, book chapters, and congress proceedings were selected if they clearly defined Olsen P threshold values for fertilizer response. This could be done on the grounds of different statistical approaches, usually linear-plateau or linear-linear fittings, Mitscherlich-type fittings (Mallarino and Blackmer, 1992; Black, 1993), or Cate-Nelson method (Cate and Nelson, 1971). For all of these methods, the relationship between relative yield, i.e., the ratio of yield in non-fertilized soil to non-P-limited yield, and the Olsen P values in soil, is established. For linear-plateau or linear-linear, the threshold value is the intersection between the two linear segments. In Mitscherlich, the threshold value corresponds to a yield of 90 or 95% of the maximum attainable yield when P is the only limiting nutrient. In the Cate Nelson, the dataset is graphically separated in two populations (one responsive and another one non-responsive), or it can be estimated as the Olsen P value that maximizes the sum of squares between two populations of Olsen P values (Geng et al., 2014; Recena et al., 2016). The expression of yields on a relative basis in the estimation of the threshold value allows the comparison of results across experiments, sites, and years (Meisinger et al., 1992; Bilbao et al., 2004).

A total of 149 cropland cases providing threshold values for different crops were identified in 37 publications. For grasslands, 69 cases were found in 10 publications. However, only clearly identified crops and sites with soil information (at least pH) were considered (83 for croplands and 28 for grasslands). The references finally used are shown in Table S1. For each selected case/site, available information on soils, including clay content, organic C content of soil, Ca carbonate equivalent, and pH ($CaCl_2$, KCl or water), and average annual rainfall and temperature was compiled. If the average rainfall and temperature were not available in the publication, it was obtained according to geographical coordinates through the web sites of https://es.climate-data.org, and https://weatherspark.com with an average of at least 9 years. To discriminate the most useful data, pH in water or in very dilute electrolytes ($CaCl_2$ in a soil-to-electrolyte ratio of 1:10) was taken into account. For all cases, except those described by Nawara et al. (2017), the pH in water was considered. In the case of Nawara et al. (2017), for soils with neutral pH and low buffer capacity (low clay content), the difference between pH in water and 0.01 M $CaCl_2$ (1:10) is expected to be minimal.

The statistical method for estimation of threshold values may have a large influence, as described by Mallarino and Blackmer (1992). Overall, a different threshold value is expected with different methods, usually in the order Cate-Nelson < Linear-linear/plateau < Mitscherlich 90% relative yield < Mitscherlich 95% relative yield. Thus, it is necessary to bear in mind homogeneous statistical methods for analysing studied cases. In most of them, the Mitscherlich-type model was used to estimate threshold values. In other cases, several statistical methods for estimating the threshold values were used; in that case, Mitscherlich was preferred, since most authors used this method. In general, this method provides the strongest explanation of the variance in relative yields with the Olsen P value (highest R^2). If only one method different from Mitscherlich was used, this was considered, but all these cases corresponded to Cate-Nelson. Overall, we took as threshold values those reported by the authors, without any additional calculation or modification, which is not possible, since we do not have access to raw data in most of the cases. Cate-Nelson allows the identification of the non-responsive population when the Mitscherlich or linear-linear/plateau fittings have poor significance. When the authors used the Mitscherlich-type model, among others, for estimating threshold values and the asymptotic limit was clearly below 90% of maximum relative yield, then threshold values for these cases were considered according to other statistical approaches and were checked with a visual Cate-Nelson approach. This occurred in 7 cases described in two studies: (i) Tang et al. (2009) (6 cases for wheat and one for maize) in which the average of the data provided by the authors was considered using linear-linear and linear plateau methods, and (ii) Sandaña et al. (2018) (1 case for potato), in which the visual Cate-Nelson was used to obtain a threshold value based on data provided by the authors in figures. Data from the Ath experiment (Belgium) provided by Nawara et al. (2017) were excluded from the analysis since the threshold values were much higher than the average of other cases (76 for barley and 61 mg kg^{-1} for potato, around three times the average for other experiments) and the non-fertilized control in this site provided around 95% of the relative maximum yield. The experiments of Poulton with wheat and Gembloux with flax described by Nawara et al. (2017) were also excluded due to the very high threshold values defined (46 mg kg^{-1} for wheat, around 4 times the average for other cases and 40 mg kg^{-1} for flax, which cannot be compared with other cases, as it was the only reference with this crop). Taking these assumptions into account, from the 83 cases of croplands mentioned above, a set of 79 cases with soil pH data, rainfall, and temperature was finally considered for statistical analysis (Table S2). Within this set, 60 cases with soil clay content were present and 59 cases included data on soil organic C content.

Table 1
Models for estimating P fertilizer requirements (adapted from Delgado et al., 2016).

Strategy	Target	Estimate of P fertilizer rate
Build up and maintenance	Soil above threshold value and replace P exportation to maintain the soil P status above threshold value	$P\ rate\ (kg\ ha^{-1}) = Exported\ P + 10\ BD\ Z\ (P_{Olsen}t - P_{Olsen}s)$ *Above threshold value, P rate = Exported P* $P\ rate < 100$ kg $P\ ha^{-1}$ P rate may decrease with increasing soil Olsen P above the threshold value; e.g. by avoiding P fertilization when Olsen P > 2 threshold value
Sufficiency	P fertilization only if SPT < Threshold value (response to P fertilization)	$P\ rate\ (kg\ ha^{-1}) = Exported\ P + 10\ BD\ Z\ (P_{Olsen}t - P_{Olsen}s)$ $P\ rate < 100$ kg $P\ ha^{-1}$ No fertilization over threshold value

$P_{Olsen}t$, Olsen P threshold value; $P_{Olsen}s$, actual soil Olsen P value; BD, bulk density (in Mg m^{-3}); Z, soil depth considered in fertilization of non-mobile nutrients (typically 0.15–0.3 m depending on crops).
The limit of total P fertilization is to avoid the enhancement of P sorption reactions that may decrease the efficiency of applied P in increasing soil available P and P uptake by crops.
The term $10\ BD\ Z\ (P_{Olsen}t - P_{Olsen}s)$ is assumed the "build up" component intended to progressively increase the available P status of soil. It is estimated on the grounds of assuming that all applied P is transformed in bicarbonate extractable P (Olsen P). However, this does not occur and it has to be considered as an annual fertilizer recommendation till the threshold value is reached (achieved in several years, depending on the P buffer capacity of soil), and the value is defined to avoid excessive P supply for building up the soil available P.

In the case of grasslands, we used the 28 cases mentioned above for the analysis.

2.2. European soil database

We used the LUCAS soil project (https://esdac.jrc.ec.europa.eu/projects/lucas) with the information published for the 2015 sampling campaign. In this database for the EU-28 (including the United Kingdom), the following soil parameters are available: texture, pH, organic C, electrical conductivity, and soil nutrient test, including Olsen P values. We used soil data of agricultural fields with two categories: "croplands" and "grasslands", with 8946 and 4751 soil samples included, respectively.

2.3. Estimation of P fertilizer needs

Strategies for estimating P needs are described in Table 1, with indication of the calculation method. In both strategies, soils below threshold values have a "build-up component" that is added to crop P exportations. This building component is designed to progressively increase Olsen P in soil until the threshold value is reached avoiding excessive P rates in only one year. However, this increase can take many years and a periodic control of P Olsen in the soil is recommended. For its estimate, the bulk density of soils is necessary, and a soil depth of 25 cm was chosen for the calculations. There is no European data set on soil bulk density. Therefore, we used the pedotransfer function proposed by Hollis et al. (2012) based on a European set of topsoils from 333 croplands. For each LUCAS soil sample, the bulk density was estimated according to this function using organic C and texture data. The estimated average bulk density was 1.38 and 1.23 Mg m^{-3} for croplands and grasslands, respectively.

The total P required for the "build-up component" can be estimated on a European scale on the grounds of the agricultural surface ascribed to each P rate class. These classes were calculated based on the current Olsen P value and the estimated threshold for each case. We can assume

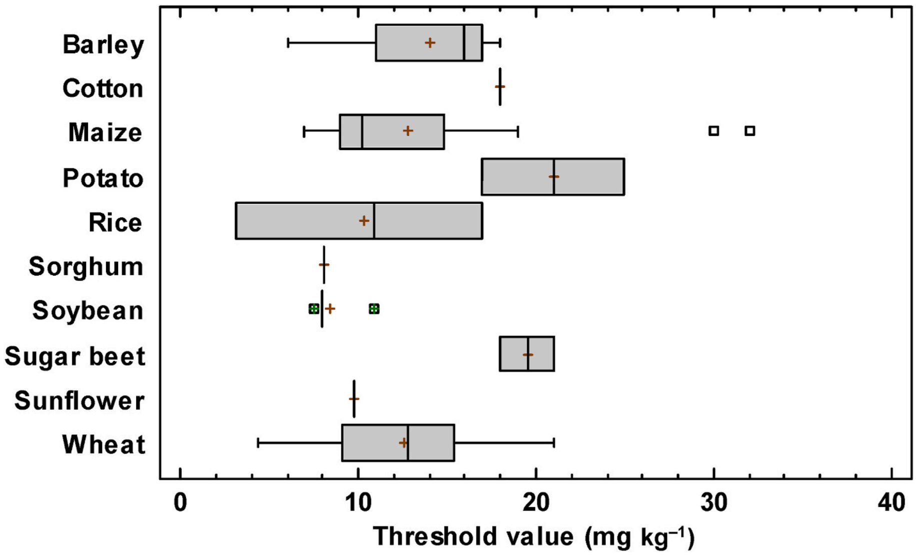

Fig. 1. Box and whisker plot of the Olsen P threshold values for P fertilizer response for different crops in croplands (n = 79). The effect of agricultural use on threshold values was not significant, and the effect of crop in croplands was significant according the Kruskal-Wallis non-parametric test (P = 0.034). In the case of rice, the threshold value is very low in the case of paddy soils (lowland rice). Excluding rice, Q1-Q3 values are in the range 9–25 mg kg^{-1}.

that the LUCAS project dataset is representative of all cropland and grassland in Europe. The agricultural surface in the European Union (2016, EU-28, including the United Kingdom) accounted for 175.2 million ha in 2015 (https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/trends-eu-agricultural-land-within-2015-2030), 66% of this corresponding to croplands (including permanent crops) and 34% to grasslands. The relative frequency of each P rate category (with mean values differing in one unit, 1 kg P ha^{-1}) was multiplied for cropland's and grassland's total surface to estimate the surface with a given P requirement. The sum of the P requirement for each category was assumed to be the total P demand for the build-up component in EU-28 including the United Kingdom.

To estimate P needs in croplands, it is necessary to take into account P export with crops. For the major crops (49) in the EU-28 in 2015 (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_crops), the P export was estimated by multiplying the exportable yield by its usual P concentration according to USDA data compiled by Delgado et al. (2016) and Helin and Weikard (2019). The estimate of grassland P exportation was made on the ground of the grassland surface in different climatic zones with different productivity according to the CORINE land cover database of the year 2000 (Tóth et al., 2014), assigning an average productivity per zone according to Smit et al. (2008), and considering an average P concentration in grass and fodder of 3 g kg^{-1} (Panagos et al., 2022).

2.4. Statistical analysis

The study of the effect of the factors 'land use' (cropland or grassland) and 'crop' on threshold values was first performed using the Kruskall-Wallis test to evaluate median differences instead of the general linear model procedure (GLM) using Statgraphics Centurion XVIII software (Stratgraphics Technologies, 2018). Although data of threshold values were normally distributed, a non-parametric test was preferred given the differences in the dispersion data for each category of crop and land use.

The relationship between threshold values and soil properties, rainfall, temperature and crop was studied using the GLM and with multiple regressions based on the least squares method when only quantitative independent variables were taken into account. In the case of qualitative variables, the performance of dummy variables (binary) is required for the application of the GLM. The dimension of the model, that is, the number of variables to be included, was defined using the Akaike information criterion (AIC; Akaike, 1974), and the accuracy of the model was checked by the Mallows Cp statistic (Gilmour, 1996). All the explicative variables in the regression model were significant according to the t statistic at $P < 0.05$ and were not correlated with each other. The goodness of the regression model was checked on the basis of the determination coefficient (R^2) which provides an information on the total variance explained by the model, and consequently of its predictive power (Altman and Krzywinski, 2015) and the root mean square error (RMSE), which provides an absolute measure of the predictive accuracy of the model. Good models should provide high R^2 and low RMSE. The mean absolute error (MAE), i.e., the mean of absolute values of the difference between predicted and actual values, was used as the estimate of the prediction error.

Predictive models were validated by leave-one-out cross-validation (LOOCV) using partial least squares (Wold, 1980). Leave-one-out is an iterative method that starts by using as a training set all the available observations except one, which is excluded for use as validation. The process is repeated as many times as there are available observations. This avoids the limitation of a non-extensive dataset (60 cases including soil pH and clay content), for selecting a training set and a validation set. With the cross-validation, R^2 and predicted R^2 of the model are compared to assess if there is overfitting in the model i.e., if predicted R^2 are clearly lower than R^2, the model fails to predict future observations reliably.

The root square mean error (RMSE) was used to estimate the confidence levels for the prediction of the observed values (prediction intervals). The upper confidence level for the prediction (relevant for defining a threshold value) at 90% can be estimated as the predicted value + 1.3 RMSE (1.3 = t value for a tailed distribution and $\alpha = 0.1$). The test to assess the significant differences between regressions was performed using the same software described above. To this end, a new regression with joint data of both regressions was performed with the introduction of a categorical variable. The interaction between the categorical variable and the explicative variable was evaluated to check the null hypothesis, i.e., no differences between the regression coefficients, by means of an analysis of variance.

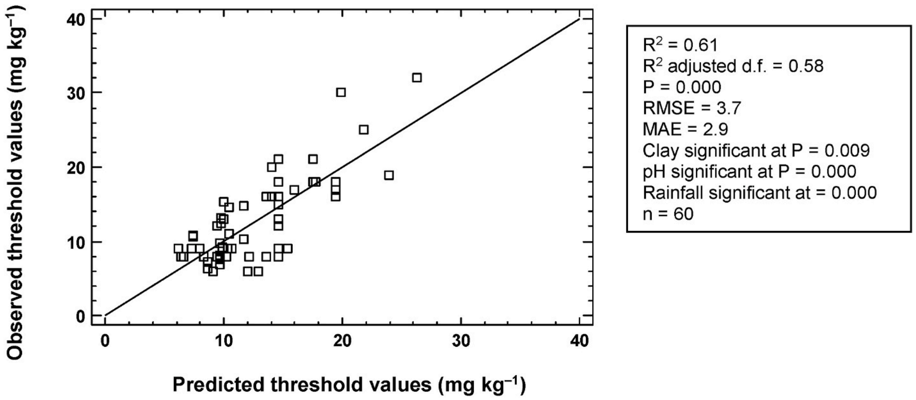

Fig. 2. Multiple regression for explaining the effect of soil clay content, pH and rainfall in croplands on Olsen P threshold values (Y = 51.5–0.011 Clay – 4.3 pH–0.008 Rainfall). Threshold values have a normal distribution according to the Kolmogorov-Smirnov test ($P < 0.05$). RMSE, root mean square error; MAE, mean absolute error.

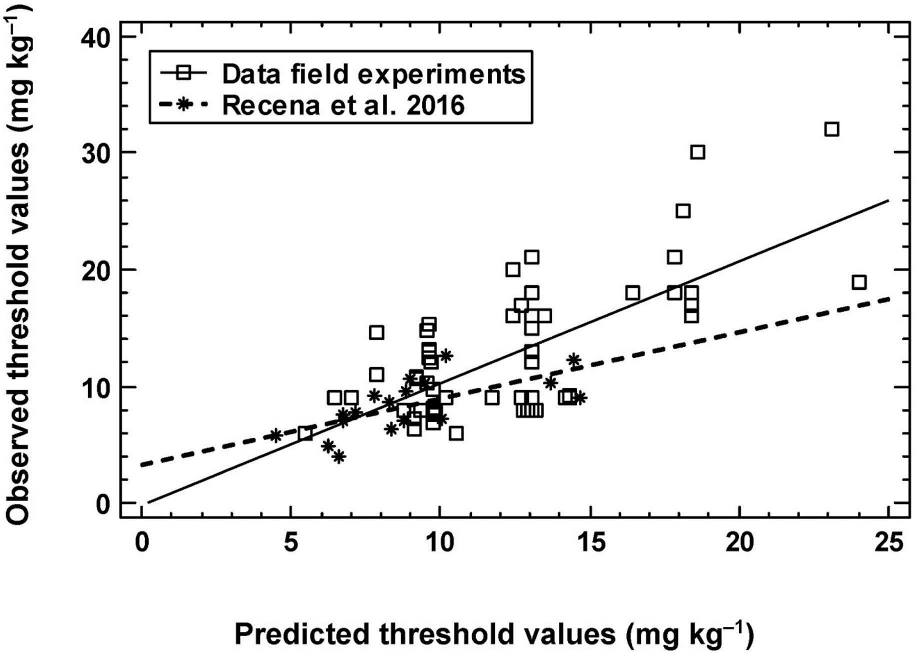

Fig. 3. Estimation of Olsen P threshold values for fertilizer response with the model for studied cases based on field experiments (solid line): Y = 43.7–0,016 Clay – 3,81 pH; R^2 = 0.49; P = 0.000; n = 60) RMSE = 4.1; MAE = 3.4. Clay significant at P = 0.001, and pH significant at P = 0.000.
This model (intercept and slope) is not significantly different from that obtained by Recena et al. (2016) in a pot experiment: Y = 36–0.012 Clay – 3.75 pH; R^2 = 0.81; P = 0.000 (n = 16) (dotted line).
RMSE, root mean square error; MAE, mean absolute error.

3. Results

3.1. *Olsen P-threshold value for fertilizer response in different crops*

The soils in the studied cases showed a wide range of properties. For croplands, the pH ranged between 4.7 and 8.6 (n = 79), soil organic C from 3.2 to 83 g kg^{-1} (n = 59), clay content from 50 to 610 g kg^{-1} (sandy to clay textures, n = 60), annual rainfall from 263 to 1535 mm and average annual temperature from 4.6 to 26.9. For grasslands, the ranges were: pH 4.5–7.9, clay 182–580 g kg^{-1}, soil organic C 15.3–553 g kg^{-1}, and annual rainfall 668–1591 mm (Table S2).

In the 79 cropland cases finally included in the analysis, the P threshold values ranged between 3.2 and 32 mg kg^{-1} (Fig. 1). The lowest value corresponded to lowland rice, cultivated under flooding. The upper (Q3) and lower quartile (Q1) were 16 and 9 mg kg^{-1}, respectively, which provides an idea of the range of more usual values. In the case of grasslands (n = 23), the threshold values varied in the range 5.3–36.1, with Q1 and Q3 of 12.4 and 19.4 mg kg^{-1}, respectively.

The effect of agricultural use (croplands or grasslands) was not significant according to the Kruskall-Wallis test. The different crops had a significant effect on the Olsen P threshold values according to this test (Fig. 1; P = 0.034). Overall, tuber and root crops showed higher threshold values than cereals. The Q1-Q3 range in cereals was 8.1–17 mg kg^{-1}, meanwhile that for potato and sugar beet was 17–25 mg kg^{-1}. The average Olsen P for sugar beet and potato (20.3; n = 4) was higher than that of cereals (12.6; n = 67) or pulses (soybean, 8.4; n = 6), and industrial crops showed intermediate values (13.9; n = 2). When the analysis was performed excluding root and tuber crops, there was no significant effect of the crop on the Olsen P threshold values (not shown); however, most of the cases (67 of 79) corresponded to cereals. The average Olsen P threshold value for maize was influenced by two high values, while the median value was the lowest among cereals (Fig. 1).

3.2. *Estimation of the Olsen P threshold values*

In the data set that included the soil clay content (n = 60), the best model to predict the threshold values involved the soil clay content and pH and the annual rainfall, explaining 61% of the variance in the threshold values (Y = 51.5–0.011 Clay – 4.3 pH–0.008 Rainfall; Fig. 2).

Table 2
Models for estimating Olsen P threshold values.

Approach	Model (threshold values in mg kg^{-1})
Croplands	
Conservative[a]	Y = 49–0.016 Clay – 3.81 pH
Minimal[b]	Y = 43.7–0.016 Clay – 3.81 pH
Graslands	
Conservative[c]	19.4
Minimal[d]	14.9

Clay in g kg^{-1}; pH in water or dilute electrolyte (1:10 $CaCl_2$).

[a] Estimated threshold values according to models in Fig. 4 are increased by 1.3 x RMSE in order to include the 90% confidence levels of the predictions.

[b] Estimate of the average values according to models in Fig. 4; in this case, it should be taken into account the risk of infra-estimation (the mean absolute error of the regression model is 3.4).

[c] Lower limit of the upper quartile of values of grassland cases (n = 23).

[d] Average value of all the grasslands cases.

Predicted R^2 in the LOOCV with the best combination of components was 0.55, slightly lower than the R^2 of the model (0.61). Thus, there is no significant overfitting, and we can assume that the model can reliably predict future observation. When clay content and pH were the only explicative variables in the model, 49% of the variance in threshold values was explained with a mean absolute error of 3.4 mg kg^{-1} (Y = 43.7–0,016 Clay – 3,81 pH; Fig. 3). This regression model was not significantly different from the previous work in pots of Recena et al. (2016). For the regression model, predicted R^2 in the LOOCV was 0.42, and consequently it can be considered reasonable to predict future observations.

When crop was included in the GLM in addition to clay, pH, and rainfall, its effect was not significant. Organic C of the soil or the temperature did not have any predictive value for the Olsen P threshold values. In all cases, the models clearly worsened if grassland data were included. When GLM was performed only for grasslands, there was no significant relationship between Olsen P threshold values and any explicative variable mentioned above.

3.3. *Status of phosphorus availability in European soils*

With a conservative approach, the confidence levels for the prediction of the threshold values for crops were defined at 90% (Table 2). Thus, a low risk of having a real threshold value higher than that estimated with the model can be assumed. Under a sufficiency fertilization strategy, i.e., P fertilization only when soil Olsen P is less than the threshold value, this minimizes risks of P deficiency in crops. In the cases of grasslands, since there was no possible prediction based on soil or climatic properties, the upper quartile was taken as the threshold value under a conservative approach.

On the European scale (Fig. 4), the estimated threshold values in croplands based on clay content and pH of soils increased from south to north and from east to west. This reflects the geographical distribution of both soil properties affecting threshold values for fertilizer response.

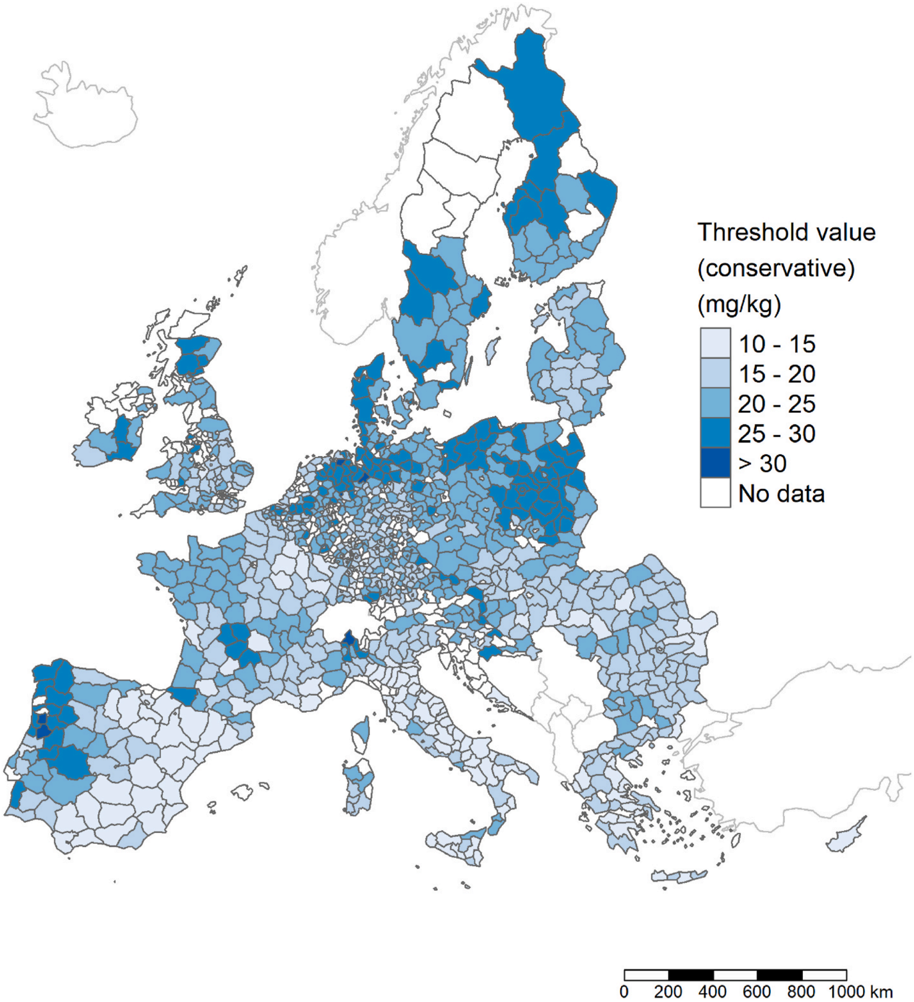

Fig. 4. Distribution of Olsen P threshold values for croplands in the European Union (EU-28 including United Kingdom). The figure represents median values by NUTS3 regions according to the conservative model for threshold value estimation based on soil clay content and pH proposed in Table 2.

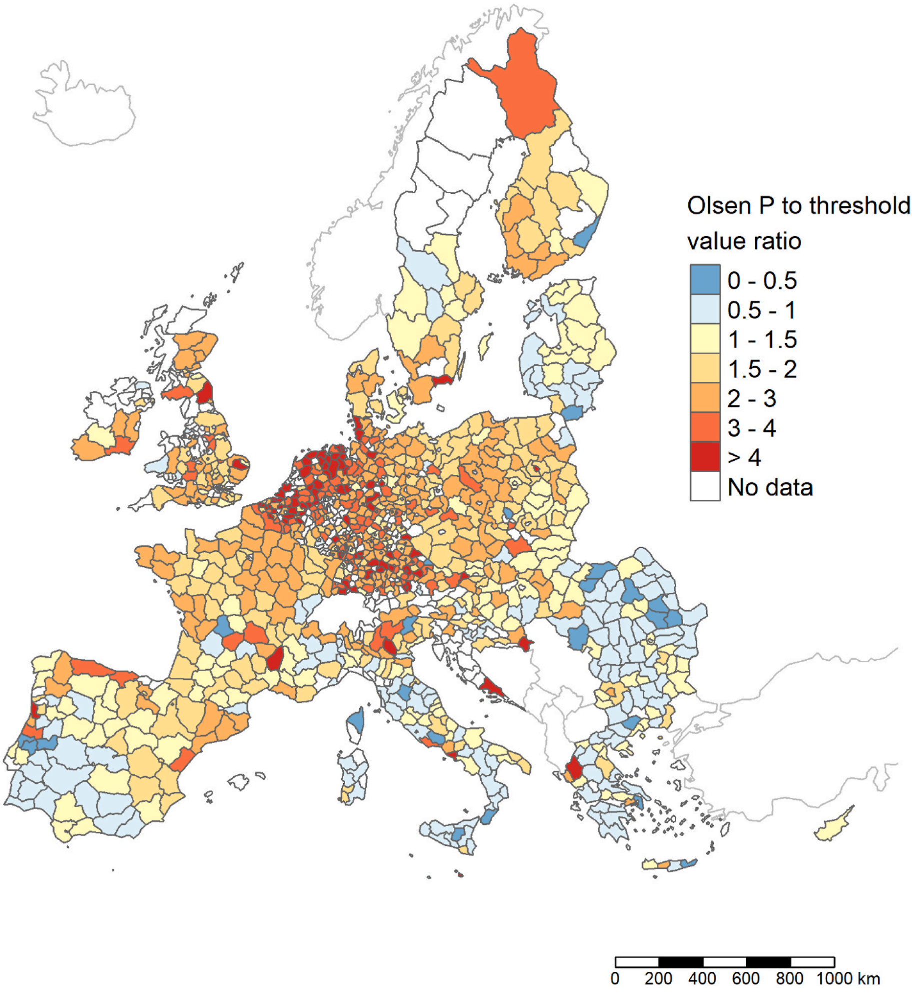

Fig. 5. Olsen P to threshold values ratio for croplands in the European Union (EU-28 including United Kingdom). The figure represents median values by NUTS3 regions according to threshold values estimated according to the conservative model based on soil clay content and pH (Table 2).

When conservative approach estimates were applied to the LUCAS cropland soil dataset used in this study, only 27.8% of the soils were P-responsive (Olsen P to threshold value ratio <1), while 39.3% had Olsen P values greater than twice the threshold values (Fig. S1; Table S3). In the grasslands soil set, 42.7% of the soils were P-responsive and 29.8% showed Olsen P values higher than twice the threshold values (Fig. S2; Table S3). When the analysis was done by country, relevant differences were found in the ratios of Olsen P to the threshold value for croplands (Fig. 5, descriptive statistics in Table S3). Overall, Belgium and the Netherlands showed median values of the Olsen P to threshold value ratio of around 4. In Germany, these values were frequently around 3. On the other hand, the Olsen P values were frequently below threshold values (ratios <1) in Bulgaria, Greece, Lithuania, Romania and Portugal (Fig. 6). For grasslands, the situation was very similar, with Benelux countries showing median values of the Olsen P to threshold value ratio higher than 3 (Fig. 6). Overall, the lowest Olsen P values in soil relative to the threshold values were found in some Eastern and Mediterranean countries. Between crops, potato and sugar beet tended to be clearly overfertilized, with the lower quartile of the Olsen P to threshold value ratio well above 1 (Table S4). Between cereals, maize was the crop showing the highest Olsen P to threshold values ratios, also with the lower quartile above 1. Some horticultural crops (orange, strawberry) were also clearly overfertilized.

3.4. *Phosphorus fertilizer needs in Europe*

The total demand for P in croplands in the EU was estimated according to the build-up and maintenance strategy, i.e., as the sum of the build-up component and the crop P exportation. With soil and land surface data for 2015, the build-up component was estimated at 760 and 378 Gg of P for croplands and grasslands, respectively (Tables S5 and S6). Except in the southwest of the Iberian peninsula, central and southern Italy, Greece, Bulgaria, and Romania, the build-up component of the fertilizer requirements was zero (Fig. 7). Therefore, in these regions with a zero build-up component, soil fertility is expected to be sustained under a build-up and maintenance strategy that supplies equivalent amounts of P to crop exportations. With a sufficiency strategy, agricultural production can be maintained for some time without the supply of P fertilizers. In the case of grasslands, most of the southern and eastern European regions require a significant supply of P as a build-

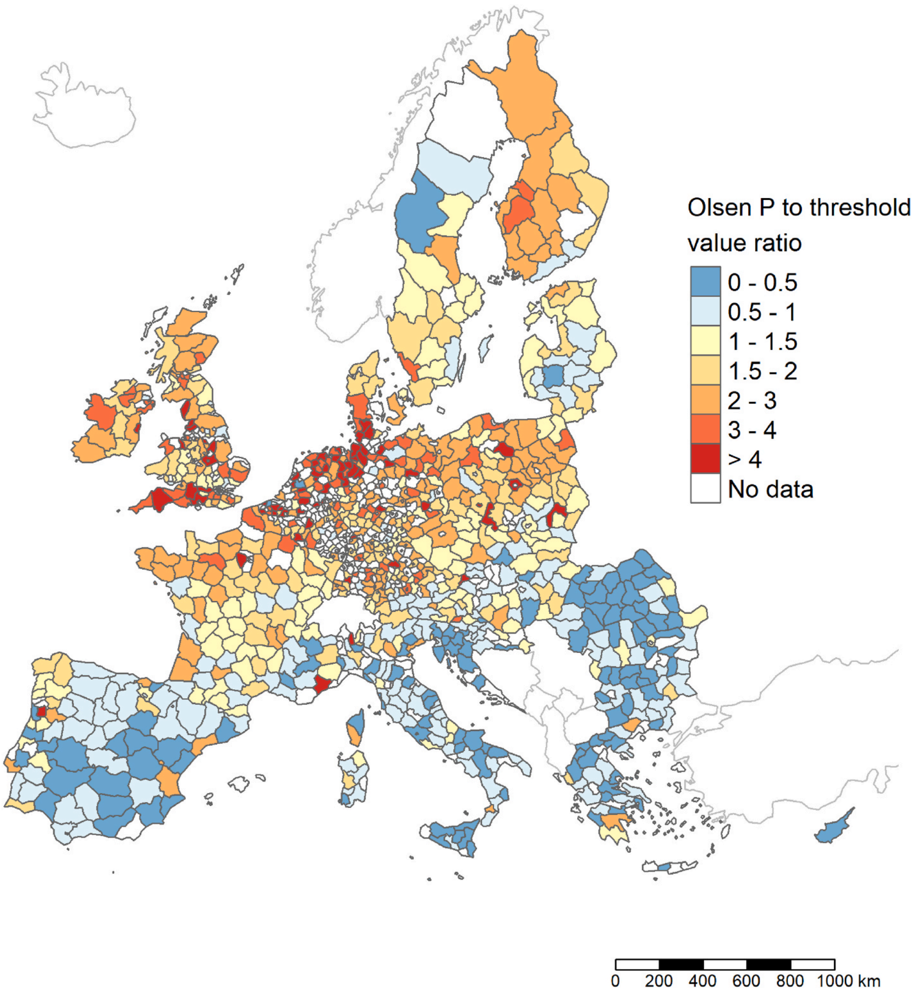

Fig. 6. Olsen P to threshold values ratio for grasslands in the European Union (EU-28 including United Kingdom). The figure represents median values by NUTS3 regions according to threshold values estimated according to the conservative model (Table 2).

up component of the total P fertilizer rate (Fig. 8). The estimated P export was 1228 Gg for 49 major crops in the EU-28 (Table S7) and 965 Gg in grasslands in 2015 (Table S8).

4. Discussion

4.1. *Identification of P-responsive sites*

Environmental factors appeared to be more relevant than crops in explaining Olsen P threshold values. However, despite the high average value for root and tuber crops, the results were not fully conclusive, as the data set was clearly dominated by cereals. The Olsen P threshold values were reasonably predicted with a regression model that included clay, pH, and annual average rainfall as predictive variables. This model explained 61% of the variance in threshold values, with a very reasonable MAE (2.9). Thus, this verifies our hypothesis of estimating the Olsen P threshold value using routinely determined soil properties and climatic variables, but not based on crops. This also reveals that climatic factors affect threshold values, since there is a negative effect of rainfall on the estimates of the Olsen P threshold values. An increase in biomass production is expected under rainfed conditions with increased rainfall, which may imply an increase in the demand for P by crop. However, the reasons for this negative effect of rainfall may be attributed to the effect of the soil water content on the movement of P to the roots. Matar et al. (1992) described an increase in Olsen P threshold values with increased aridity in Mediterranean environments. This was explained because P in the soil solution mostly moves to the roots by diffusion, which is reduced when the soil is dry. In addition, a decrease in the soil water contents implies an increase in the ionic strength in the soil solution. This enhances P adsorption in soils when the pH is above a certain value (Bolan et al., 1986), affecting the equilibrium between the solid and water phases and decreasing the release of P from the sorbent surfaces. Thus, it seems that a more constant humidity in the soil improves the use of P by crops, reducing the threshold values for fertilizer response. This reveals the need to consider the climatic conditions in each growing season. Furthermore, increased aridity, as a consequence of climate change, would mean higher threshold values and less efficient use of P by crops. The extreme situation is lowland rice cultivation under flooding, where the reduction of P sorbent surfaces may explain very low threshold values (3.2 mg kg^{-1}).

Almost half of the variance (49%) in the threshold values was explained if only clay content and pH were included in the model, with a MAE of 3.4. It should be noted that this model was not significantly different from that previously described by Recena et al. (2016) using a pot experiment growing wheat and sunflower. It can be assumed that with an accurate estimate of threshold values, Olsen P can be deemed a valid soil P test for acid soils.

The negative effect of clay content on Olsen P threshold values has been ascribed to the positive correlation usually found between clay content and P buffer capacity (Recena et al., 2016). The threshold value decreases with increased P buffer capacity (Ehlert et al., 2003; Delgado et al., 2010) since the soil can keep the P concentration more constant

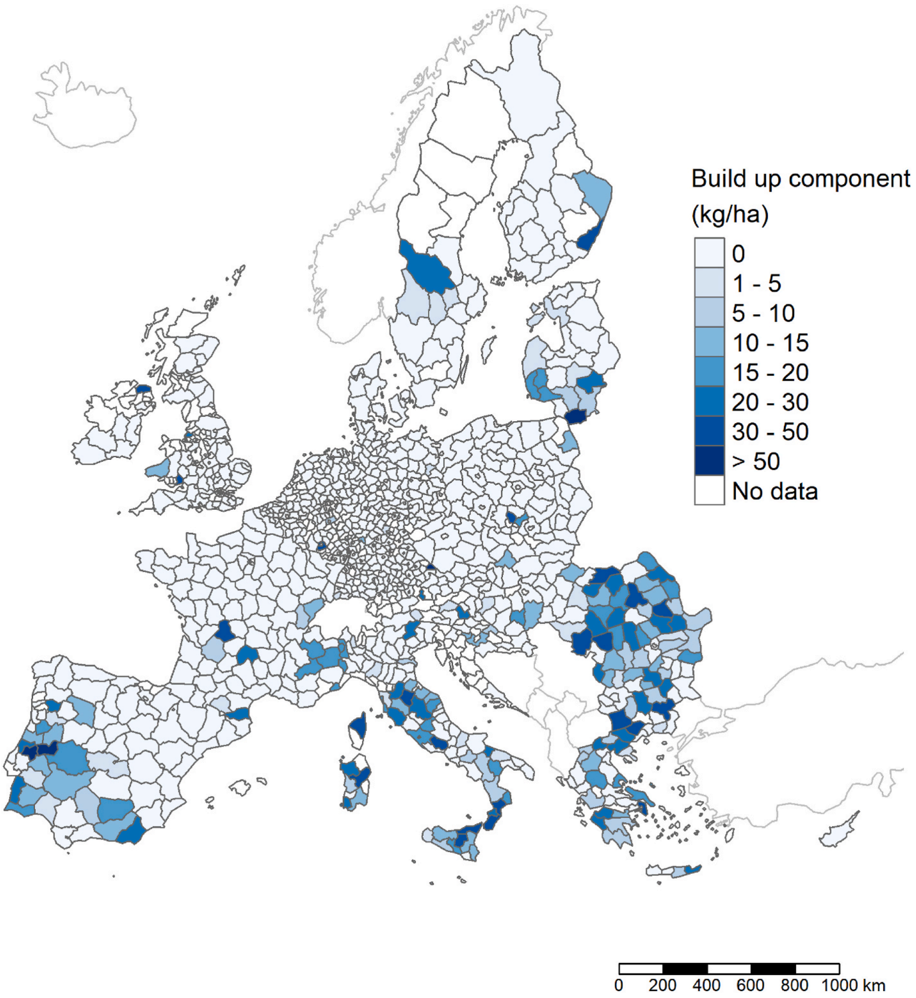

Fig. 7. Build up component of the fertilizer P rate in croplands according to the fertilizer strategies described in Table 1 in the NUTS3 regions of the European Union (EU-28 including United Kingdom). A build up component of zero implies that under an "Increase and maintenance strategy" the P fertilizer should compensate crop P exportations, and under a "Sufficiency strategy", no fertilization is required.

due to P desorption after P uptake by plants. Additionally, threshold values decrease with increased P sorption capacity, which is generally positively correlated with clay content (Recena et al., 2016). The negative effect of pH on Olsen P threshold values has been ascribed to its influence on soil P dynamics and its correlation with other soil properties such as the type of sorbent surface that affects P availability to plants (Delgado and Torrent, 1997). Thus, the use in the predictive model of soil properties related to its P buffer and sorption capacity seemed crucial to achieving reasonably accurate estimates of Olsen P threshold values.

The Olsen P threshold estimation model has uncertainties. The main one is likely the variability in the determination of Olsen P values between different laboratories as Jordan-Meille et al. (2012) described. Thus, accurate analytical protocols are also required for large-scale recommendations based on the Olsen P method. Another uncertainty is that the model takes into account crop type but not crop rotations. It is known that preceding crops can affect P availability to plants (Lukowiak et al., 2016), but this information was not always available in the dataset used for the model. Analysis of soil P status in Europe was carried out with the model based on soil clay and pH (Fig. 3) since it was not easy to find reliable and current information on average annual rainfall at all sampling points of the LUCAS project. Additionally, rainfall is the most changeable predictive factor, and annual variation can be significant in affecting crop response to soil P. This lack of precise information on rainfall also contributes to uncertainty in the model. However, the mechanistic support of the model seemed solid, since the results based on the literature review were fully consistent with the results obtained under the environmental controlled conditions described by Recena et al. (2016). Furthermore, cross-validation supported a reliable estimate of future observations.

4.2. Status of soil P in Europe

In general, we found a high general P level in a representative set of European soils, 72.2% of croplands and 57.3% of grasslands being not P-responsive taking the starting point in 2015. When analyzed by countries, the very high levels of Olsen P values compared with threshold values found in some countries of western and central Europe reflect the consequences of the balance of P fertilizers in European soils, with less overfertilization in grasslands than in croplands (Tóth et al., 2014; Van Dijk et al., 2016). The comparison between countries based on Olsen P values was done by Tóth et al. (2014) using the LUCAS project database (with the 2009 dataset). However, this comparison was made on the basis of absolute values and not on the Olsen P-to-threshold value ratio for each specific site. This may lead to a likely overestimation of high-P sites, since areas with high Olsen P values according to the LUCAS project database frequently correspond to soils with low clay content and pH (e.g., The Netherlands). In these soils, the threshold values for fertilizer response are assumed to be higher than in soils with a high pH and clay content. However, in soils from south and eastern Europe, with

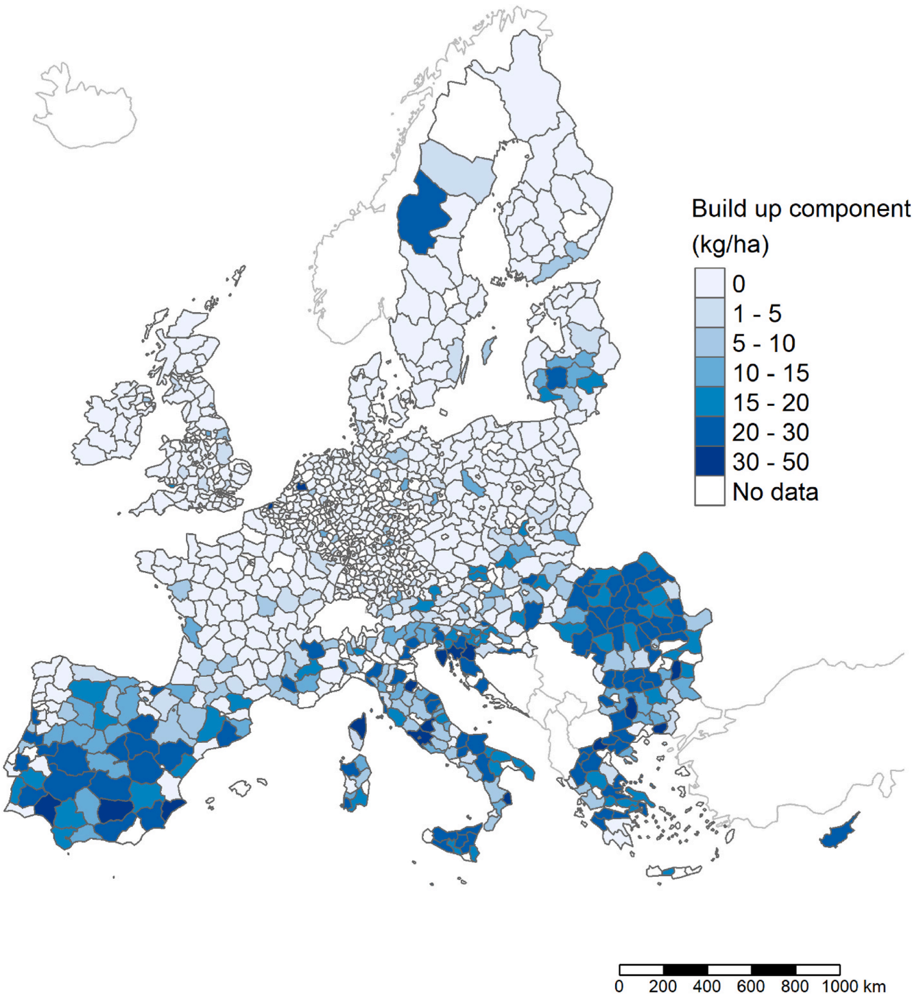

Fig. 8. Build up component of the fertilizer P rate in grasslands according to the fertilizer strategies described in Table 1 in the NUTS3 regions of the European Union (EU-28 including United Kingdom). A build up component of zero implies that under an "Increase and maintenance strategy" the P fertilizer should compensate crop P exportations, and under a "Sufficiency strategy", no fertilization is required.

the lowest average Olsen P values, P-responsive sites may be overestimated since soils with high pH and clay content, thus with lower threshold values, are more frequent in these areas. However, in these latter cases the median of Olsen P to threshold value tended to be much lower than the mean (Table S3), indicating that the mean value is affected by a reduced number of very high values. Consequently, soils with an Olsen P-to-threshold value ratio lower than 1 are more frequent in the southern and eastern regions of the EU (Figs. 5 and 6).

The highest Olsen P to threshold value ratio was observed in crops with high biomass yield and high P uptake: potato, sugar beet, and maize (Table S4). This means that farmers' perception of a high P uptake led to overfertilization of these crops. However, the average ratio of Olsen P to threshold value in potato and sugar beet seemed to be influenced by extremely low values, while that of maize seemed to be influenced by extremely high values. The latter seems to be the case for most crops. All of this revealed wide variations in the amount of P fertilizers applied to a given crop within the EU, leading to wide differences in the available P status of the soil.

4.3. Phosphorus fertilizer needs in Europe

Regions with a build-up component equal to zero (Figs. 7 and 8) are those with the highest positive P balance (Tóth et al., 2014), frequently attributed to the application of high manure rates. The total estimated amount for the build-up component is not far from the annual P enrichment (positive balance of 924 Gg) of agricultural land in the EU estimated by Van Dijk et al. (2016). However, this current enrichment is not necessarily allocated to P-responsive sites. This reveals the need for a better allocation of the P resource on the continental scale to reduce the excessive enrichment of P in agricultural soils in some regions and consequently the environmental problems ascribed to this enrichment. Furthermore, a more precise allocation of P resources will increase agricultural productivity in P-responsive sites.

The annual demand for P to build up the P reserve until it reaches the threshold value in soils below it amounted to 1138 Gg of P for EU-28 in 2015 (croplands + grasslands). We estimated 1228 Gg of P export for main crops and 965 for grasslands in the EU-28, which is a total of 2193 Gg of P, in 2015. This roughly agrees with the estimate of P removal by crops and grasslands described by Panagos et al. (2022) for the EU-28 (including the UK) in 2016, and with Van Dijk et al. (2016), who estimated P export from agricultural land at 2300 Gg for the EU-27 in 2005. This means that for a build-up and maintenance strategy, the annual total P demand is around 3330 Gg (1138 of the build-up component + 2193 as maintenance component), roughly equivalent to the total P applied in 2005 as manure and mineral fertilizers according to Van Dijk et al. (2016) or in 2015 according to the European Commission (https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/market-brief-fertilisers_june2019_en.pdf). This is the scenario with the highest P demand based on a P fertilization strategy to build up and maintain. The estimated total demand according to this strategy does not mean a decrease compared to the total P fertilizer applied to European agricultural soils. However, our proposal accounts for an increased allocation of resources to P-responsive sites based on the use of Olsen P. With time, the P enrichment of P-responsive sites will lead to a decrease in the demand for P fertilizer in Europe.

4.4. A circular economy approach to decreasing mineral P fertilizer demand in Europe

Returns to agricultural land from human consumption, food processing, and manure account for around 1900 Gg y^{-1} (Van Dijk et al., 2016). Losses in human food consumption, food and non-food processing were around 1070 Gg in 2005 (van Dijk et al., 2016). Thus, 2970 Gg of P y^{-1} can be recycled from agricultural systems, food processing and urban residues (wastewater and urban solid wastes) for using in agriculture. This would be enough to cover a large part of the P fertilization needs estimated above under the scenario with the highest demand based on a build-up and maintenance strategy. This means that mineral fertilizer needs would be reduced from around 1200 (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_mineral_fertiliser_consumption#Analysis_at_EU_level) to around 330 Gg y^{-1}. However, this need will decrease in the future if the P resources are utilized in P responsive sites as mentioned above. Our estimate is a starting point defined in 2015 according to the available LUCAS dataset. The main constraint to achieve this circular economy-based strategy is the logistic requirement to use sources (bio-based fertilizers) with low P concentration or the new knowledge required to concentrate P in these materials. However, a circular economy approach in the use of P will have benefits that should be taken into account as offsets of the mentioned constraints. Valorising residues will contribute to solving their management problems. On the other hand, recycled P forms, in particular organic sources, can increase available P in soil more efficiently than soluble mineral fertilizers through an effect of organic matter blocking P adsorption sites and precipitation in soils (Delgado and Scalenghe, 2008) and may induce benefits on soil quality (Moreno et al., 2016).

5. Conclusions

Identification of P-responsive sites in EU-28 (including the UK) is possible using a simple model for the estimation of Olsen P threshold values involving soil properties routinely determined in soil analysis (clay and pH). This will allow for a better allocation of P resources and more accurate estimates of P fertilizer rates as a basis for sustainable fertilization schemes. This will lead to a decrease in P fertilizer needs in the future by increasing P levels in P-responsive sites while decreasing excessive enrichment in non-P-responsive sites and the associated environmental impact. The estimated demand for P in Europe based on this information indicated that it is possible to cover most of this demand (86%) by optimizing the recycling of P from food processing, manure, wastewater, and municipal solid waste. The proposed method for identifying P-responsive sites and the circular economy approach in the use of P will contribute to agricultural sustainability, food security, and environmental performance in the use of this resource.

CRediT authorship contribution statement

Ramiro Recena: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Ana M. García-López:** Methodologymethodolgy, Formal analysis. **José M. Quintero:** Conceptualization, Methodology. **Annaliina Skyttä:** Visualization, Formal analysis. **Kari Ylivainio:** Writing – review & editing, Conceptualization. **Jakob Santner:** Writing – original draft, Conceptualization. **Else Buenemann:** Writing – original draft, Conceptualization. **Antonio Delgado:** Conceptualization, Formal analysis, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134749.

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