Thresholds of target phosphorus fertility classes in European fertilizer recommendations in relation to critical soil test phosphorus values derived from the analysis of 55 European long-term field experiments

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Abstract

Phosphorus (P) fertilizer recommendations of individual countries may differ in many aspects, but often the main principle is to reach or maintain a target range of plant-available P in soil. Within this target P fertility class, the soil is expected to supply enough P to the crop, while P fertilization replaces what is exported by the harvested crop. However, the threshold values of the target P fertility classes are based on a multitude of different soil test P (STP) methods and vary by a factor of up to three, even for countries using the same STP method. This study aimed to provide a comparison of the thresholds of target P fertility classes of different European countries and critical soil test P values (P_{crit}; STP below which the average relative yield falls below 95% due to P insufficiency) derived from the analysis of data from 55 long-term field experiments in eight European countries. To overcome the issue of diverging STP methods, all values were converted to Olsen-P using empirically based conversion equations from the literature. Converted threshold values varied by a factor of up to five. For the experimental data, we fitted multi-level Mitscherlich-type models to determine P_{crit} values of unfertilized soils corresponding to 95% of maximum yield. We found an average Olsen-P_{crit} value of 15 mg P kg^{-1} (adj. R^2 = 0.37; RMSE = 14.1; n = 2368; 55 experiments), which lies far below several country-specific thresholds of target P fertility classes. Crop-specific analyses resulted in higher Olsen-P_{crit} values for sugar beet (22 mg P kg^{-1}), potato (19 mg P kg^{-1}) and winter rapeseed (18 mg P kg^{-1}). Among the texture classes (loam, sand, silt and clay), sandy soils exhibited the highest average Olsen-P_{crit} value (22 mg P kg^{-1}). We

consider a reevaluation of extraordinarily high country-specific thresholds as well as an inclusion of crop type and soil texture (where not already implemented) to be a reasonable measure towards more cost-effective and environment-friendly P fertilization.

Keywords: Phosphorus, Olsen-P, Critical soil test P, P fertilization, Fertilizer recommendation

1. Introduction

Phosphorus is an essential, often growth-limiting nutrient for plants, and thus P fertilization is crucial for agricultural production (Ruttenberg, 2003; Ashley et al., 2011; Schoumans et al., 2015; Sharpley et al., 2018). In Europe, decades of high P fertilization rates, exceeding P export by crops, led to excessive accumulation of P in many agricultural soils (Sattari et al., 2012; Rubæk et al., 2013; Ringeval et al., 2014; Tóth et al., 2014). In recent years, growing environmental concerns as well as increased awareness of P as a non-renewable resource have led to efforts for achieving more sustainable P fertilization (Buczko and Kuchenbuch, 2007; Cordell et al., 2009; Fischer et al., 2017).

In many European countries, there is no direct P legislation concerning fertilizer rates. Regulation is merely indirect by the European Water Framework Directive, Good Agricultural Practice or erosion control (Amery and Schoumans, 2014; Garske et al., 2020). However, there are almost always country-specific fertilizer recommendations (Jordan-Meille et al., 2012).

Optimal fertilization schemes should guarantee optimal yields, while minimizing fertilizer costs and environmental impacts. According to a sufficiency approach, even a total omission of fertilization should be considered to use legacy P more efficiently, if this does not have a negative effect on yields (e.g., Olson et al., 1987). In practice, most fertilizer recommendations are based on the principle of a target range of plant-available P in soil, which should be reached or maintained (build-up and maintenance approach). Various soil test P (STP) methods are used to determine STP values as a proxy for plant available P (Jordan-Meille et al., 2012; Schick et al., 2013; Nawara et al., 2017).

In the target P fertility class, soils are supposed to supply enough P to crops. When soils are in this class, the objective of fertilization is to maintain STP values. This means P rates equivalent to P export by crops, assuming that no significant loss of P fertilizer occurs. In P fertility classes above the target class (excessive classes; high STP values), it is in general suggested to reduce fertilizer application. For STP values below the threshold of the target P fertility class, application of P rates exceeding uptake by crops is recommended with the purpose to increase STP values over time. In contrast to sufficiency approaches, build-up and maintenance approaches therefore usually recommend fertilization for all STP levels except the highest fertility class.

In both approaches, the definition of thresholds for yield response can be expected to be based on critical STP values (P_{crit}) of some sort. Those are STP values below which the average relative yield falls below a given value, e.g., 95%, due to P insufficiency. Since the threshold of the target P fertility class in fertilizer recommendations usually also represents the STP value below which yield may be restricted due to P insufficiency, this threshold should be related to a P_{crit} value. Above this threshold, there will be no considerable changes in yield, except for possible negative yield effects due to extreme overfertilization. This lack of yield response at higher STP levels makes the basis for the definition of excessive classes less clear, with possible influencing factors being additional economic or ecological considerations. Therefore, the thresholds of the target P fertility class, available in various recommendation schemes, are the most useful benchmarks for comparing and evaluating recommendation schemes throughout Europe.

Indeed, thresholds of target P fertility classes in most recommendation schemes in European countries are deduced from field experiments recording yield response to increasing STP values. They are mostly empirical, focused on assurance of crop yields and rarely take environmental issues into account (Kuchenbuch and Buczko, 2011; Jordan-Meille et al., 2012; Buczko et al., 2018). In some countries, there are variations in thresholds or recommended P fertilizer rates depending on, e.g., crop type or soil texture (e.g., Albertsson, 2008; Richner and Sinaj, 2017). The data and approaches used to develop thresholds and recommendations are rarely published (Jordan-Meille et al., 2012). Those factors impair the transparency and comparability of different thresholds. Furthermore, there is a large number of different STP methods in Europe, whose values cannot be compared directly.

Since a general revision of STP methodology as well as more transparency of calibration approaches seem unlikely in the near future, attempts to compare fertility classes and the corresponding fertilizer recommendations have to circumvent these problems. Comparative studies of different European P fertilizer recommendations have been published by Fotyma et al. (2008) and Jordan-Meille et al. (2012). For the comparisons in these publications, soil samples, in combination with information on the crop and the expected yield, were submitted to laboratories of different countries. Then, the P fertilizer rates, recommended by the different laboratories for the same soils, were compared, revealing large differences. Due to influences of different recommendation schemes, e.g., increased rates for specific crops, these approaches do not necessarily make thresholds of target P fertility classes comparable.

In the present study, we aim to compare different European recommendation schemes based on the thresholds of the target P fertility class converted to Olsen-P. We think that thresholds of target P fertility classes, as a major influence on recommended P rates, should be based on more solid and transparent experimental evidences. Assuming that the P_{crit} value is a reasonable point to where the threshold of the target P fertility class should be set, we conducted an analysis of yield response to STP based on data from multiple European long-term field experiments (LTFEs). Additionally, we evaluated the influence of crop type and soil texture.

2. Material and methods

2.1. STP methods and conversion equations

An overview of the characteristics of the applied STP methods is given in Table 1. A numerical comparison between thresholds of target P fertility classes based on different STP methods requires the conversion of results from different methods. Since the Olsen method is the method used most frequently in scientific literature as well as in the countries considered and also for a high share of the experimental data forming the base of this study, we converted all other STP values into Olsen-P. The Olsen method was developed for alkaline soils, but it also offers reasonable results for other soils (e.g., Horta et al., 2010; Wuenscher et al., 2015).

The methods Mehlich-3, AAAc-EDTA and CAL feature similar extraction mechanisms, resulting in relatively high correlations between STP values derived by these methods. The methods Olsen (the only alkaline solution; Table 1), AAAc, DL, H_2O and H_2O-CO_2 show more diverging extraction mechanisms, leading to often weaker correlations between methods (e.g., Neyroud and Lischer, 2003; Schick et al., 2013; Shwiekh et al., 2015; Steinfurth et al., 2021). In case of methods with very different extraction mechanisms, it should be emphasized that soil properties, in particular pH or carbonate content, have a large impact on conversion results (e.g., Eriksson et al., 2013; Shwiekh et al., 2015). Therefore, the selection of conversion equations, stemming from soils of similar pH or carbonate content, should be strived for.

In general, conversion equations found in literature are strictly empirical and highly dependent on the soils used to establish the equation. To select the most appropriate conversion equations for our study, we used a review of conversion equations (Steinfurth et al., 2021). For the conversion of LTFE data, we aimed for equations based on soil samples comparable to the soils of the LTFEs. Due to a lack of data on carbonate contents, equations based on soils of similar pH and soil texture were chosen. For the conversion of country-specific thresholds, equations based on various soils of that country were preferred. For both, LTFE data and thresholds, equations corresponding to these criteria were not always available. For the conversion of H_2O-CO_2-P to Olsen-P, only one equation was available and therefore, this equation was used. Where multiple equations were available, equations leading to extremely high or low Olsen-P values were avoided, favoring, e.g., the medium one of three different coefficients. Regression equations with very high intercepts (often a result of right-skewed data; Neyroud and Lischer, 2003) were avoided to be able to include low Olsen-P values. More details are given in Steinfurth et al. (2021). The selected equations are listed in Table 2.

In case of the AL-method, where an equation including pH value and clay content was selected for conversion (Table 2; Otabbong et al., 2009), we used site-specific values for the conversion of data from the LTFEs, since we had access to this information. For the conversion of the country-specific P thresholds given in form of AL-P (Belgium (Flanders), Norway, Sweden), we used the mean pH_{H2O} value (6.45) and clay content (17.4%) of the soils included in the corresponding study (Otabbong et al., 2009).

2.2. Thresholds of target P fertility classes

Depending on the availability of the according documents, information on threshold values for the target P fertility classes in the fertilizer recommendation schemes of different European countries and the used STP methods were obtained from the respective recommendation documents, specific publications or from the information given in Jordan-Meille et al. (2012). Not all of the considered recommendation schemes or thresholds are official, neither are they necessarily the only ones used in respective countries. Instead, they are often the ones best known or openly available. Detailed references are given in Table 3.

Where possible, we identified the target P fertility class as the one in which fertilization equal to export is recommended. Most often this was the medium fertility class (e.g., class three out of five), but not always. Deviations, e.g., crop or soil dependencies, are stated in the footnotes of Table 3. Where soil-(or crop-) specific thresholds are present, values listed in Table 3 are average values. Threshold values according to STP methods other than Olsen were converted using the equations listed in Table 2.

2.3. LTFE data

Data from 55 LTFEs in eight European countries were included (Fig. 1, Table 4). Data were collected in the years 1968 to 2018 and cover a broad range of STP values. Clay contents range from 2.8 to 46.5%, organic carbon contents from 0.67 to 2.7% and pH_{CaCl2} values from 4.5 to 7.8 (Table 5). Where pH values were measured in a soil suspension of water instead of a solution of $CaCl_2$, a conversion was conducted according to Eq. 1:

$$pH_{CaCl2} = pH_{H2O} - 0.59 \text{ (SD: 0.10)} \quad (1)$$

This equation was deduced from the Swedish Lanna field experiments (Lanna 1936 and Lanna 1941), where both methods were used (n = 90, pH_{CaCl2}: 5.2–7.0; pH_{H2O}: 5.9–7.7). This is in accordance with a difference between both methods of 0.6 (±0.2) pH units, as given in standard soil science textbooks (Blume et al., 2016). This conversion was done for direct comparability of pH values only. For conversion (and selection of conversion equations) between STP methods, non-converted pH values were used, since pH was measured with the appropriate method in all cases. Therefore, results of this study were not affected by pH conversion.

Crops considered in this study are grain maize, oat, pea, potato, sorghum, spring barley, spring wheat, sugar beet, winter barley, winter rapeseed, winter rye and winter wheat. Other crops were excluded due to their rare occurrences among sites and years. Soil sampling depth ranged between 0.2 and 0.3 m, mostly depending on the depth of the plough layer (e.g., Rubæk and Sibbesen, 2000; Morel et al., 2014; Zicker et al., 2018). If STP was not measured every year, the value of the closest year with measurements was utilized.

In addition to treatments without P fertilization, many experiments examined more than one P fertilizer treatment, e.g., fertilizer rate corresponding to half of P export, equal to P export and double of P export. All other nutrients were supplied in sufficient rates to be non-limiting for optimum plant growth. To avoid effects of other nutrients or input of organic matter as far as possible, treatments fertilized with manure were excluded. P fertilization took place with superphosphates (superphosphate, double superphosphate, triple superphosphate).

For the joint analysis of data from different locations, crops and years, the use of relative yield values is the usual procedure (Speirs et al., 2013; Nawara et al., 2017; Gourley et al., 2019). The treatment with the highest P fertilizer rate for a specific year of an experiment was used as a reference, assuming yields of these highest fertilized treatments are equivalent to maximum attainable yield (Nawara et al., 2017). While some extremely high fertilizer rates (up to 211 kg ha^{-1} $year^{-1}$) were included, there was no indication of yield depression due to over-fertilization with P.

Since the focus of this study lies on STP values, we aimed to avoid influences of different fertilizer rates as far as possible. While fertilizer rates and STP are closely connected by P balance over time, different yield response for treatments with the same STP value but different rates of applied P fertilizer cannot be ruled out (e.g., Valkama et al. 2011). Therefore, only yields of unfertilized treatments (n = 2368) were compared to yields attained with the highest P fertilization rate of the same experiment and year.

Where several replicates (exact same treatments within the same year) were available, mean values (always for a specific year) were used. Some experiments offered several observations (combinations of an unfertilized and corresponding maximum fertilized treatment) per year, due to additional differentiation by e.g., different crops, liming treatments, handling of straw or fertilization history. These were not considered as replicates, but as separate sub-experiments.

This data preparation resulted in 2368 observations i.e., (sub-)experiment-year-combinations, each including yield and STP of the unfertilized and the corresponding maximum fertilized treatment plus the corresponding relative yield (RY), calculated according to Speirs et al. (2013; Eq. 2):

$$RY = Yield_{unfertilized} / Yield_{maximum\ fertilized} \times 100 \quad (2)$$

2.4. Data analysis

The compiled data were used to fit a modified Mitscherlich model (Eq. 3):

$$RY = 100 \times (1 - \exp(- c \times Olsen\text{-}P)) \quad (3)$$

The coefficient *c* defines the steepness of the yield increase in response to increasing Olsen-P. The value 100 represents the expected asymptote of 100% of maximum yield.

Whereas other studies used Mitscherlich-type models with intercepts (e.g., Poulton et al., 2013; Nawara et al., 2017; Hirte et al., 2021), we used a model without an intercept. The reason for this was few low Olsen-P data in many of the included experiments, resulting in unreliably high y-intercepts (high predicted RY at 0 mg kg^{-1} Olsen-P). Since studies including very low Olsen-P values show yield near zero for Olsen-P values near zero (e.g., Poulton et al., 2013), we chose to force the function through the origin (see also discussion section 4.2.1.).

The coefficient *c* was estimated via maximum likelihood. For this, we used a multi-level approach with the different experiments as random effects to account for autocorrelation and overrepresentation due to varying numbers of observations provided by each experiment (Hox, 1998; de Leeuw et al., 2008). Additionally, crop types and main soil texture classes (clay, loam, sand and silt; Eckelmann et al., 2005) were set as fixed effects to investigate their impact on the coefficient c.

Individual analyses were also conducted for the experiments of single countries to portray the potential variation of results based on different groups of experiments.

The country-specific analyses are by no means representative for soils of the entire country.

The analyses were conducted in R (Version 4.1.1; R Core Team, 2021) with the package nlme (Pinheiro et al., 2021). The Akaike information criterion (AIC) was used to identify which explicative variables should be included in the model, striving for minimum AIC (Portet, 2020). Observed RY was plotted against the predicted RY to determine the adjusted coefficient of determination (adj. R^2) of the fit (Piñeiro et al., 2008; Nawara et al., 2017). Root Mean Square Error (RMSE) was calculated to evaluate the quality of prediction. The standard deviation of the coefficient *c* (SD_c) presents a measure for variability between experiments.

In a next step, we calculated critical Olsen-P values (Olsen-P_{crit}) corresponding to a RY of 95% (Eq. 4):

$$Olsen\text{-}P_{crit} = \ln(-95/100 + 1) / -c \qquad (4)$$

As a threshold for significant yield response to Olsen-P, 95% of maximum yield (average loss of 5% of yield) was set in accordance with values used in similar studies (Morel et al., 1992; Nawara et al., 2017; Gourley et al., 2019). This Olsen-P_{crit} was used as a benchmark for the evaluation of the country-specific thresholds of the target P fertility classes. The 95% confidence intervals of the Olsen-P_{crit} values were deduced from the corresponding intervals of the coefficient c.

3. Results

3.1. Country-specific thresholds of target P fertility classes in fertilizer recommendations

Thresholds of target P fertility classes of different country-specific fertilizer recommendations showed large variations. Moreover, the inclusion of additional parameters like crop type, soil texture or clay content led to varying thresholds for different crops or soils (e.g., France and Switzerland; Table 3).
Thresholds of target P fertility classes, originally given as Olsen-P, lay between 10 (Italy) and 31 mg P kg^{-1} (France). The conversion of all values to Olsen-P resulted in a range of 10 (Italy) to 55 mg P kg^{-1} (Belgium (Flanders)). Thus, the thresholds of the target P fertility classes varied by a factor of more than five between countries (Table 3).

3.2. Analysis of LTFE-data

The joint analysis of data with STP values originally measured with the Olsen method resulted in an average Olsen-P_{crit} of 16 mg P kg^{-1} soil. An analysis also including data converted from other methods showed a similar Olsen-P_{crit} of 15 mg P kg^{-1}. The adj. R^2 value of the model based only on data measured with the Olsen method was higher than for the model including converted data (0.57 vs. 0.37; Fig. 2), while SD_c (based on differences between experiments) and RMSE were similar for both models (SD_c: 0.103 and 0.111; RMSE: 15.4 and 14.1% RY).
Separate analyses of data from single countries (Fig. 3) revealed a large variety of Olsen-P ranges and also large scatter of the experimental data. The resulting Olsen-P_{crit} values, ranged between 7 (Swiss experiments) and 26 mg P kg^{-1} (Austrian experiments). The Swedish experiments showed a very low adj. R^2 value of 0.031 with large scatter of RY in a relatively narrow Olsen-P range (Figure 3). Nonetheless, the resulting RMSE of 18.5% RY is not much higher than for data of the UK (18.4% RY) with an adj. R^2 of 0.54. This implies that the observed Olsen-P range is just too

small and unfavorably situated to show a clear pattern of yield response to varying Olsen-P.

In some cases, the combined data did not show a visible decrease of RY with decreasing Olsen P (Fig. 3; Austria, Denmark), although some individual experiments do (e.g., Grabenegg (Alpenvorland) and Ødum). This was accompanied by relatively low adj. R^2 values (0.18 for the Austrian and 0.15 for the Danish experiments). Experimental data from France, Switzerland, and the UK resulted in better model fits (adj. R^2 between 0.29 and 0.81) than for the Austrian and Danish data. They also showed a more pronounced RY decrease with decreasing Olsen-P, including a higher share of data in very low Olsen-P ranges. For the data from France, Switzerland and the UK, the values of Olsen-P_{crit} ranged between 7 and 11 mg P kg^{-1}, and were thus below the value derived from the function based on all countries combined (15 mg P kg^{-1}). The high adj. R^2 value of the French experiments (0.81) was accompanied by a relatively high SD_c. This portrays large differences between experiments while the scatter in the rather small number of observations was low.

The inclusion of the crop type as a fixed effect (for the whole dataset, including values originally determined using the Olsen method as well as converted values) improved the model. More specifically, AIC decreased from 19388 to 19222, adj. R^2 increased from 0.37 to 0.43 and RMSE decreased from 14.1 to 13.5% RY. Winter wheat was chosen as a reference (intercept of the coefficient; c = 0.252, Olsen-P_{crit} = 12 mg P kg^{-1}). Potato, sugar beet and winter rapeseed showed significantly lower c values and accordingly higher Olsen-P_{crit} values (18 to 22 mg P kg^{-1}; Fig. 4). Grain maize and winter barley exhibited slightly higher (14 mg P kg^{-1}), sorghum, spring barley and spring wheat slightly lower (9, 10 and 10 mg P kg^{-1}) Olsen-P_{crit} values compared to winter wheat. For oat, pea and winter rye, the model did not significantly improve prediction in comparison to an intercept-only model (regression model without predictors). Therefore, no Olsen-P_{crit} values were calculated for these crops. The use of soil texture classes as a fixed effect (with loam soils as the reference/intercept) resulted in a significantly lower coefficient *c* and accordingly a higher average Olsen-P_{crit} value for sandy soils compared to loam soils. Sandy soils showed a coefficient c of 0.138, an Olsen-P_{crit} value of 22 mg P kg^{-1}, an adj. R^2 value of 0.24 and a RMSE of 8.6% RY. Loam soils showed a coefficient c of 0.241, an Olsen-P_{crit} value of 12 mg P kg^{-1}, an adj. R^2 value of 0.50 and a RMSE of 13.3% RY. Clay (c = 0.223; Olsen-P_{crit} = 13 mg P kg^{-1}; adj. R^2 = 0.02; RMSE = 17.9% RY) and silt soils (c = 0.200; Olsen-P_{crit} = 15 mg P kg^{-1}; adj. R^2 = 0.20; RMSE = 16.5% RY) did not significantly differ from the intercept of loam soils. The use of other texture classes as the intercept, revealed no additional significant differences. Except for loam with a range of 10 to 16 mg P kg^{-1}, the texture classes showed large 95% confidence intervals of Olsen-P_{crit} with a range of 14 to 54 mg P kg^{-1} for sandy soils, 9 to 29 mg P kg^{-1} for clay and 10 to 32 mg P kg^{-1} for silt soils. In spite of the differences, soil texture class as the only fixed effect did not improve the model (AIC = 19391; adj. R^2 = 0.37; RMSE = 14.1% RY).

A combination of crop types and texture classes as fixed effects without interactions (AIC = 19227; adj. R^2 = 0.43; RMSE = 13.6% RY) did not improve the model compared to only crop type as a fixed effect (AIC = 19222; adj. R^2 = 0.43; RMSE = 13.5% RY). Including interactions between crops and texture classes, it was not possible to fit a model.

4. Discussion

4.1. Reliability of converted STP values

The use of conversion equations between methods will always be a source of error. Conversion equations for one pair of STP methods often vary strongly (e.g., for AL-P to Olsen-P: Schachtschabel, 1973; Lončarić et al., 2006; Otabbong et al., 2009; Shwiekh et al., 2015). The equations are highly dependent on the soils used to establish the equation and therefore their reliability for other soils is limited. Additionally, there are discrepancies between laboratories using the same STP method (Neyroud and Lischer, 2003; Kleinman et al., 2001; Rubæk, 2015). Nonetheless, based on a critical review (Steinfurth et al., 2021), we tried our best to choose the most appropriate conversion options to enable the joint analysis of data from this high number of different experiments.

Many recommendation schemes are meant to be valid for all soils of the corresponding countries (without differentiated thresholds for different soil types). Therefore, for the conversion of country-specific thresholds, we find it appropriate to choose the most average equations, avoiding those leading to comparably high or low Olsen-P values (often due to special features of the underlying soils).

For the conversion of the experimental data, we chose equations based on soils as similar as possible to the soils of the specific experiments. While the possibly induced error should be kept in mind, the similar outcome of the models for the data directly measured with the Olsen method vs. data including converted values (Fig. 2) points to a high reliability of the conversion-based results. There are differences between different groups of experiments (Fig. 3), but these also occur between countries using the same STP method. Therefore, they probably have additional sources of variability than merely conversion errors.

4.2. Models

4.2.1. Type of Mitscherlich equation

Fitting Mitscherlich-type models without intercept results in fitted yields of zero at an STP of zero. In practice, yields as well as STP values of zero are rarely found and it might be possible, that zero yield is already reached at an STP value above zero or that there is still yield when there is no P measurable by the chosen STP method. This often leads to the use of Mitscherlich-type models allowing for intercepts (e.g., Poulton et al., 2013; Nawara et al., 2017; Hirte et al., 2021). Model fitting with intercepts will usually lead to higher (adj.) R^2 values, but those intercepts are only reliable with good data coverage in low STP ranges. Concerning Olsen-P, there are studies allowing for intercepts, which still result in functions nearly meeting the coordinate origin (e.g., Tang et al., 2009; Poulton at al., 2013). In addition, there are examples of studies using Mitscherlich-type models forced through the coordinate origin (e.g., Pukhovskiy, 2013; Gourley et al., 2019).

Allowing for an intercept in this study led to experiments with low Olsen-P data showing rather low, often not significant intercepts. In contrast, many experiments with few low Olsen-P data showed significant, high y-intercepts (high predicted RY at 0 mg kg^{-1} Olsen-P). Here, the lack of RY decrease in rather high Olsen-P ranges (mostly above Olsen-P_{crit}; RY values near the asymptote) led to the false assumption that RY would always stay stable. The use of a Mitscherlich-type model without intercept restricted this problem and its influence on the overall result. Without an intercept, values near the asymptote just indicate that in the given range of Olsen-P values, an Olsen-P at which RY decreases is not yet reached. At the same time, it is clear that it will be reached before 0 mg kg^{-1} Olsen-P. In order to enable a joint analysis of all experiments, we committed to a general use of a Mitscherlich-type model without intercept (Eq. 3).

4.2.2. Models without differentiation by country, crop or soil texture

The similarity of average Olsen-P_{crit} values derived from data originally measured with the Olsen method (16 mg P kg^{-1}; n = 731; Fig. 2) and all data, including converted values (Olsen-P_{crit} = 15 mg P kg^{-1}; n = 2368; Fig. 2), implies a similar average response of RY to decreasing Olsen-P throughout the experiments. In order to include as many data points as possible, we therefore used all data (i.e., both, originally measured with the Olsen method and converted data) for further analysis. The lower adj. R^2 value of the model including converted values should not surprise given the higher number of included experiments with accordingly wider range of soil properties and crops (Fig. 2). While the resulting adj. R^2 values appear to be rather low, they actually are similar to values of comparable studies (e.g., Nawara et al., 2017; Gourley et al., 2019).

Our average Olsen-P_{crit} values lie slightly below values found in similar studies. An analysis using data from five European countries (data partially also included in our database) conducted by Nawara et al. (2017) determined a mean Olsen-P_{crit} value of 19 mg P kg^{-1} soil for all experiments, treatments and crops combined (Mitscherlich-type function, R^2 =0.49, Olsen-P_{crit} refers to 95% of RY). Studies of Johnston et al. (2013) and Poulton et al. (2013), based on experiments conducted in the UK (data partially also included in our database), showed an average Olsen-P_{crit} of 18.5 mg P kg^{-1} (mean of individual values from both studies). For these studies, Mitscherlich-type functions were used with a threshold of RY of 98% (with a few exceptions where the threshold of RY was 95%), being higher than in our study and thus leading to higher Olsen-P_{crit} values.

4.2.3. Individual countries

The experiments of the individual countries are not representative for soils of the corresponding countries. Therefore, it is not feasible to reevaluate country-specific thresholds based on those results alone. However, the portrayal of these groups can serve as an example of how the composition of a database can affect the results. The large range of country-specific average Olsen-P_{crit} values (7 to 26 mg P kg^{-1}) can be attributed to different influencing factors like cultivated crops, prevailing soil types, climate, attainable yield level or Olsen-P range of the experiments. As an example, the Austrian (26 mg P kg^{-1}) and Danish (24 mg P kg^{-1}) experiments show rather high average Olsen-P_{crit} values while including a rather low share of very low Olsen-P values. The insufficient extent of low Olsen-P data may limit the estimation of reliable P_{crit} values.

This lack of very low STP values is not surprising, since STP values are often high at the beginning of the experiments due to decades of prior P fertilization. It takes many years to decrease STP (Johnston et al., 2016), even at zero fertilization, especially since often a carryover of soil from plot to plot by tillage occurs (Sibbesen et al., 2000). Often, individual experiments portray a very small STP range and only the combination with other experiments manifests a visible saturation curve. In combination with factors like different soil types, large differences between experiments can occur e.g., the large SD_c for the French experiments (Fig. 3) or Sorghum (Fig. 4).

The Austrian data demonstrate that 100% of RY (represented by the yield of the maximum fertilized treatment) are not always reached on unfertilized plots, even at very high Olsen-P values (Fig. 3). This effect can be expected due to an influence of recently applied fertilizer that is not present on unfertilized plots. It should be kept in mind, that under build-up and maintenance approaches, fields with STP in the optimum range are still fertilized according to the P export by the crop to maintain the current STP value. Although fertilization is usually not taking place annually, it can be assumed to close the gap between the expected asymptote of 100% and actual RY.

For recommendations going for a sufficiency approach, these reduced yields at high STP values (if significant) would be much more relevant, questioning long-term omitted P fertilization even at very high STP values.

4.2.4. Differentiation by crops and soil texture

Values of STP change rather slowly over several years, making it nearly impossible to adjust STP to each crop-specific P_{crit} value in the short-term. Settling for an STP value which is sufficient for maximum yield on average, means it will be insufficient for some crops in the rotation. In addition to the STP value, recent fertilizer application can influence yield. Fertilization is often not carried out on a yearly basis, but rather in the context of a crop rotation (Baumgarten, 2017; VDLUFA, 2018). Therefore, the application of the rotation's whole P fertilizer amount (or a high share of it) before crops with higher Olsen-P_{crit} values i.e., crops which are susceptible to P deficiency, can be a reasonable concept. This is a common practice, e.g., in France (COMIFER, 2019).

The German fertilizer recommendation (VDLUFA, 2018) suggests elevated P fertilizer application for potatoes, maize, sugar beets, winter rapeseed and legumes. Except for maize (Olsen-P_{crit} = 14 mg kg^{-1}) and legumes (no Olsen-P_{crit} calculated), this resonates well with our findings, since those crops showed Olsen-P_{crit} levels higher than the average of all crops (15 mg P kg^{-1}) (Fig. 4). Potatoes indeed are considered to have a high P demand by several recommendations (e.g., Richner and Sinaj, 2017; VDLUFA, 2018; de Haan and van Geel, 2013). Johnston et al. (2013) found Olsen-P_{crit} values for individual years of potato yields ranging between 11 and 61 mg P kg^{-1} (two experimental sites; mean = 29 mg P kg^{-1}). Similarly, Nawara et al. (2017) found an extremely high Olsen-P_{crit} for potatoes (76 mg P kg^{-1}), but it should be considered that the number of observations was very low (four observations in one experiment).

Average Olsen-P_{crit} values described in the literature for barley and wheat mainly range between 12 and 24 mg P kg^{-1} (Jackson et al., 1991; Jackson et al., 1997; Tang et al., 2009; Speirs et al., 2013; Nawara et al., 2017), with our results (10 to 14 mg P kg^{-1} for spring barley, winter barley and wheat) lying at the lower limit of this range. For maize, Olsen-P_{crit} values of 8 to 18 mg P kg^{-1} have been found by Mallarino and Atia (2005), Tang et al. (2009) and Nawara et al. (2017), ranging well around our value of 14 mg P kg^{-1}. Concerning all of these comparisons, it should be kept in mind, that model type and thresholds of P deficiency (e.g., 90, 95 or 98% of maximum yield) often vary between studies and have a large influence on the results.

Morel et al. (2000) found a restriction of yield at higher phosphate ion concentrations in the soil solution for a sandy soil compared to more loamy soils. This is in accordance with a higher P_{crit} value for sandy soils compared to loam soils found in our study (sandy soils: Olsen-P_{crit} of 22 mg P kg^{-1}; loam soils: Olsen-P_{crit} of 12 mg P kg^{-1}). These differences can be partially explained by the varying P buffer capacity, which is higher in clay soils than in sandy soils (Morel et al., 2000; Recena et al., 2016). Recommendation schemes differentiating between soil textures also follow the same direction, setting thresholds higher for sandy or at least clay-poor soils (e.g., Peltovuori, 1999; Richner and Sinaj, 2017). A possible explanation for the lack of model improvement by differentiation between soil texture classes in our study is the inclusion of soil texture as part of the experiment-specific random effects in combination with the partial correction for clay content induced by the conversion of data derived by the AL method (conversion equation includes clay content as a variable; Table 2).

4.3. Reliability of average Olsen-P_{crit} values for the security of yields

At first glance, the use of average Olsen-P_{crit} values appears to be the natural choice for setting STP thresholds, which should be applicable for many different soils, crops and years. Nonetheless, the large scatter in the observed STP-yield relations should not remain unnoticed. This scatter is caused by several factors. STP values are only a proxy of plant available soil P with restricted ability to predict yield response (Nawara et al., 2017; Recena et al., 2017). Yield depends also on other influences like e.g., weather conditions or soil properties.

As an example, the Swedish experimental data show a rather small range of Olsen-P values (4.9–21.4 mg P kg^{-1}, Fig. 3), but large fluctuations of the RY and a very low corresponding adj. R^2, illustrating the poor fit of the model. Therefore, the resulting Olsen-P_{crit} value of 15 mg P kg^{-1} should be seen with caution. The data hint at decreasing RY at already relatively high Olsen-P of about 20 mg P kg^{-1}, at least for some years. Thus, they may indicate high fluctuations dependent on year-specific differences i.e., weather conditions. Studies of Johnston et al. (2013) and Poulton et al. (2013), based on individual years of experiments conducted in the UK (overlaps with our database), showed fluctuations of Olsen-P_{crit} between 6 and 61 mg P kg^{-1} soil (Olsen-P_{crit} refers to RY of 98%), depending on treatment, crop and especially weather conditions (mainly rainfall) of the individual years. This pronounced yearly variation in different experiments suggests that mean Olsen-P_{crit} values, determined as averages for several years, could possibly not be sufficient in some years, leading to yield loss.

Accordingly, it is not surprising, that some recommendation schemes aim for higher yield security, possibly based on e.g., confidence intervals or P_{crit} of the crop with the highest P demand, and therefore establish thresholds strongly exceeding our findings. Of course, such elevated thresholds will result in STP values unnecessarily high for many crop-year combinations and thus in unnecessary fertilizer costs and environmental risks. In addition to scatter towards low RY values, there is also scatter in the opposite direction. Scatter towards high as well as low RY values does not necessarily decrease towards higher Olsen-P values (e.g., Fig. 3; Austria and UK). Therefore, the uncertainty of yield often is still present at very high Olsen-P values, further reducing the advantages of increased fertilizer application.

4.4. Comparison of Olsen-P_{crit} values with country-specific thresholds of target P fertility classes

The country-specific thresholds of target P fertility classes derived from the fertilizer recommendations vary widely (Table 3). Only the thresholds of Italy, Spain and the United Kingdom lie below our average Olsen-P_{crit} value of 15 mg P kg^{-1}, all others are higher. Concerning the UK, some British studies already pointed out that their calculated Olsen-P_{crit} values lie above the threshold of the target P fertility class (Johnston et al., 2013; Poulton et al., 2013). The very high Olsen-P_{crit} value for Belgium (Flanders) is backed up by often extremely high STP values and high fertilizer use in Flanders (Tóth et al., 2014). An explanation might be very high yield levels in this area (Tóth et al., 2014) possibly increasing the threshold of yield response, plus very intensive land use with exaggerated striving for yield security. Finnish soils often have low pH values and a high content of Al and Fe, strengthening the fixation of P (Saarela, 2002; Schick et al., 2013; Shwiekh et al., 2015). Therefore, average P_{crit} values of Finnish soils may diverge from average values of other countries.

While our study was based on a modified Mitscherlich model (Eq. 3), comparing unfertilized with fertilized plots, the approaches used for obtaining the various recommendations may differ and can lead to highly differing results (Perelli, 1990;

Mallarino and Blackmer, 1992). Additional potential sources of variation are the handling of differences between crops and confidence intervals as well as the specification of RY level, e.g., 90, 95 or 99% (Colomb et al., 2007), for the corresponding STP to be accounted as P_{crit} level. Inappropriate conclusions from experimental results might be an issue, as stated for the Finnish Agri-Environmental Programme by Valkama et al. (2009). Of course, also variations in corresponding experiments will influence deduced thresholds due to different climate, soils, STP range, crops and attainable yield level. Often, it is even unclear if there is a sufficient mechanistic approach behind thresholds at all.

The country-specific split of our data demonstrated that results can vary widely even when the same response functions and thresholds of RY are used. Still, the range of average Olsen-P_{crit} values of 7 to 26 mg P kg^{-1} found in the country-specific analysis lies in the lower half of the range of thresholds of target P fertility classes (10 to 55 mg P kg^{-1} Olsen-P; Table 3).

5. Conclusions

Large differences between thresholds of target P fertility classes in European P fertilizer recommendation schemes might be explained by variations in underlying experiments, prevailing soil types, crops, climate and attainable yield levels as well as differing approaches of threshold deduction and errors induced by the conversion of STP values into Olsen-P. Nonetheless, the average Olsen-P_{crit} values determined with our database lie within the lower half of the range of thresholds and there are examples of established recommendation schemes working with relatively low thresholds of the target P fertility class. This implies that a reconsideration of those country-specific thresholds lying at the upper end of the range would be reasonable. In future, more transparency of threshold deduction would be desirable. The detected differences of yield response to Olsen-P between various crops and soil texture classes demonstrate that according differentiations, as existing for several recommendation schemes, can be useful measures towards more cost-efficient and environment-friendly P-fertilization.

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Figures

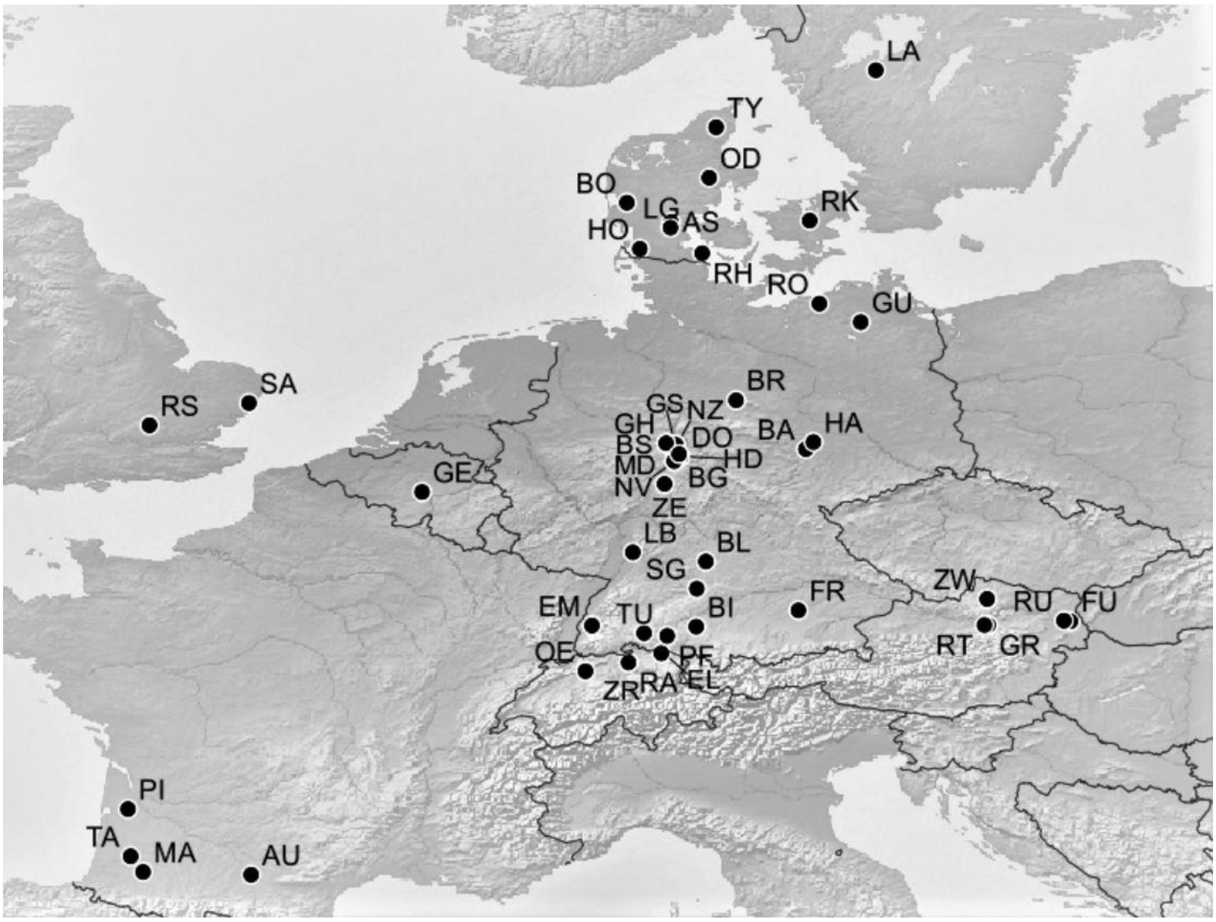

Fig.1. Locations of the field experiments included in the analysis. Abbreviations refer to locations as given in Table 4. Map created with layers of Natural Earth[a, b].

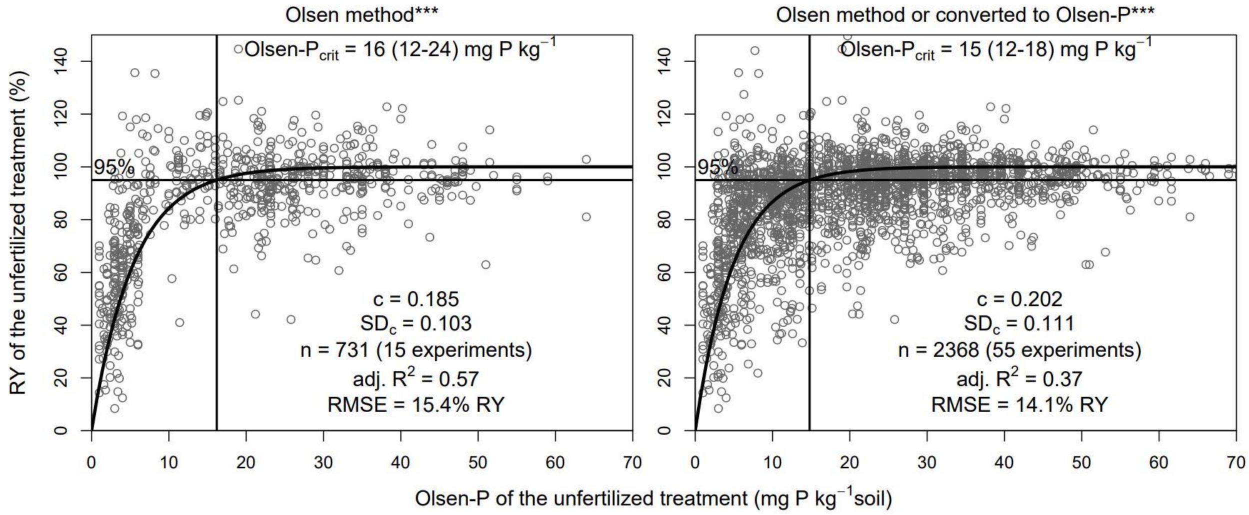

Fig. 2. Average Mitscherlich-type functions and corresponding Olsen-P_{crit} values (95% confidence interval) derived from data measured with the Olsen method (left) and data including values converted from other methods (right). Significance level of the model * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

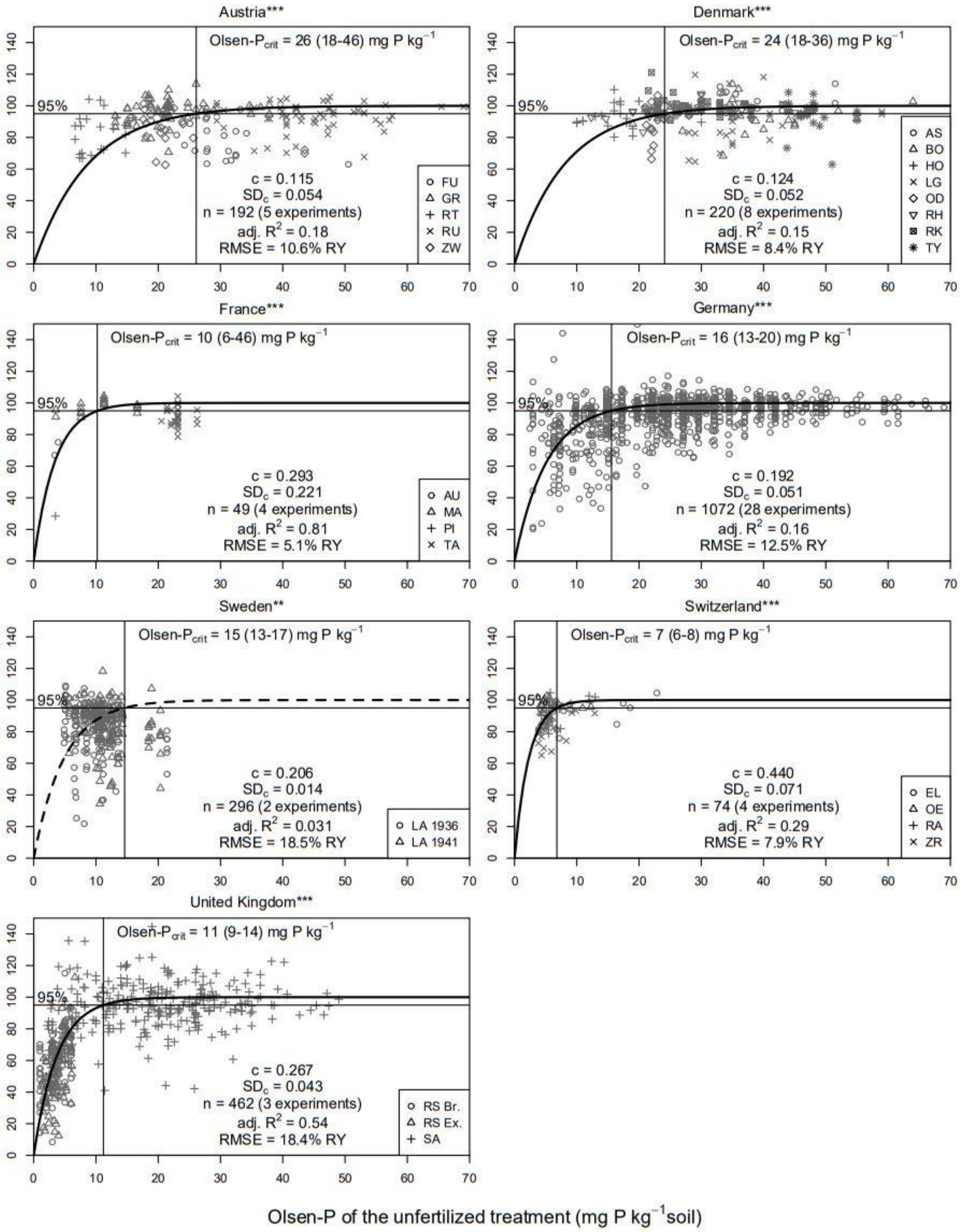

Fig. 3. Average Mitscherlich-type functions and corresponding Olsen-P$_{crit}$ values (95% confidence interval) derived from data grouped by countries. The country-specific analyses are by no means representative for soils of the entire country. Values determined with other methods than Olsen were converted according to Table 2 (Austria, Germany, Sweden, Switzerland). The clustering in the Swedish

experiments is induced by pH-specific conversion of plots with different lime treatments. Due to a lack of data (only three observations), no function was fitted for Belgium. The curve for the Swedish experiments is dashed for a very low adj. R^2 value. Abbreviations refer to locations as given in Table 4. For Germany, experiments were not differentiated due to the high number (28) of included experiments. Significance level of the model * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

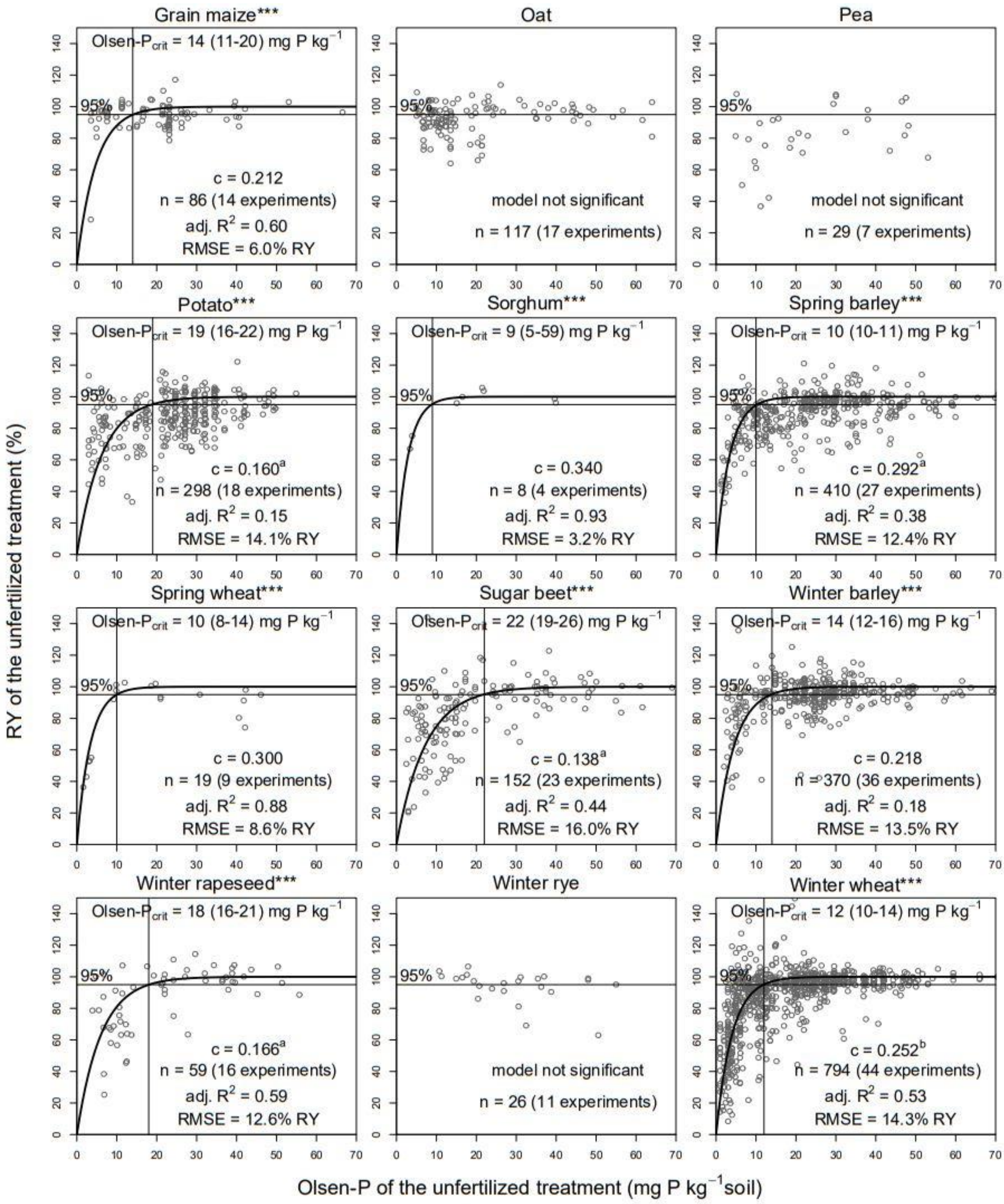

Fig. 4. Average Mitscherlich-type functions and corresponding Olsen-P$_{crit}$ values (95% confidence interval) derived by the use of the crop type as a fixed factor. Data derived from other methods than Olsen were converted according to Table 2. [a] Significantly different from the intercept (winter wheat) [b] Intercept of the model. Significance level of the model * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Tables

Table 1

Overview of the characteristics of the involved STP methods in alphabetical order (modified after Steinfurth et al., 2021).

Method	Solution	Solution pH	Soil to solution ratio	Extraction time	Reference
AAAc (acid ammonium acetate)	0.5 M ammonium acetate, 0.5 M acetic acid	4.65	1:10	60 min	Vuorinen and Mäkitie, 1955
AAAc-EDTA (Acid ammonium acetate + EDTA)	0.5 M ammonium acetate + 0.5 M acetic acid + 0.025 M EDTA	4.65	1:5 or 1:10	30 or 60 min	Lakanen and Erviö, 1971
AL (ammonium lactate)	0.1 M ammonium lactate + 0.4 M acetic acid	3.75	1:20	120 min	Egnér et al., 1960
CAL (calcium-acetate-lactate)	0.05 M calcium acetate + 0.05 M calcium lactate + 0.3 M acetic acid	4.1	1:20	120 min	Schüller, 1969
DL (double lactate)	0.02 M calcium lactate + 0.02 M hydrochloric acid	3.6	1:50	90 min	Riehm, 1943
H_2O	water (20°C)	-	1:60	60 min	Sissingh, 1971
H_2O-CO_2	CO_2-saturated water	slightly acidic	1:2.5	60 min	Dirks and Scheffer, 1930
Mehlich 3	0.2 M acetic acid + 0.25 M ammonium nitrate + 0.015 M ammonium fluoride + 0.013 M nitric acid + 0.001 M EDTA	2.5	1:10	5 min	Mehlich, 1984
Olsen	0.5 M sodium bicarbonate	8.5	1:20	30 min	Olsen et al., 1954

Table 2

Equations used for conversions from STP values obtained by various methods to Olsen-P.

Method	No.	Equation	Underlying soils	Quality	Reference	Used for
AAAc	1	$54.9 \times \text{AAAc-P}^{0.2824} - 56.9$	183 Finnish soil samples	$R^2 = 0.77$	Withers et al., 2019	Finland: Country-specific threshold
AAAc-EDTA[a]	2	$0.40 \times$ AAAc-EDTA	217 soil samples from Estonia, Finland, Germany and Poland	$r = 0.77^{**}$	Schick et al., 2013[b]	Belgium (Wallonia) + Switzerland: Country-specific threshold
AL	3	$(12.68 + 0.599 \times \text{AL-P}^{0.5} + 0.232 \times \text{Clay(\%)}^{0.5} - 1.985 \times pH_{H2O})^2$	82 Swedish soil samples	$R^2 = 0.94$	Otabbong et al., 2009	Belgium (Flanders) + Sweden: Country-specific thresholds + LTFE data; Norway: Country-specific threshold
CAL	4	$0.56 \times$ CAL-P	60 German soil samples	$r^c = 0.81^{**}$	Shwiekh et al., 2015[b]	Germany + Austria: Country-specific thresholds + LTFE data (loam soils + clay soils)
	5	$0.71 \times$ CAL-P	6 German loamy sand, sand-loess and loess soils; pH_{CaCl2} 5.1–6.1	$SD^d = 0.19$, $r^c = 0.84^{*}$	von Vetter et al., 1977[e]	Germany + Austria: LTFE data (loamy sand soils + silt soils with average $pH_{CaCl2} < 6.0$)
	6	$0.50 \times$ CAL-P	191 German loess soils, pH_{CaCl2} 4.9–7.7	$r = 0.86^{**}$	Schachtschabel, 1973[b]	Germany + Austria: LTFE data (silt soils with $pH_{CaCl2} > 6.0$)

DL	7	0.52 x DL-P	6 German loamy sand, sand-loess and loess soils; pH_{CaCl2} 5.1–6.1	SD[d] = 0.15; r[c] = 0.63*	von Vetter et al., 1977[e]	Germany: LTFE data (loamy sand soils + loess soils with average pH_{CaCl2} < 6)
	8	0.42 x DL-P	191 German loess soils, pH_{CaCl2} 4.9–7.7	r = 0.81**	Schachtschabel, 1973[b]	Germany: LTFE data (loess soils with average pH_{CaCl2} > 6)
	9	0.40 x DL-P	40 Polish soil samples	r[c] = 0.79**	Schick et al., 2013; Shwiekh et al., 2015[b, f]	Poland: Country-specific threshold
H_2O	10	3.00 x H_2O-P	217 soil samples from Estonia, Finland, Germany and Poland	r[c] = 0.78**	Schick et al., 2013[b]	Netherlands: Country-specific threshold
H_2O-CO_2	11	15.78 x $P_{H2O-CO2}$	135 soil samples from 12 European countries	NA	Neyroud and Lischer, 2003[b]	Switzerland: LTFE data + country-specific threshold
Mehlich 3	12	11.79 + 0.26 x M3-P	1089 Czech soils	R^2 = 0.69	Zbíral and Němec, 2002[g]	Czech Rep.: Country-specific threshold

[a] Varying procedure, Belgian recommendation scheme (Genot et al., 2011): soil to solution ratio 1:5, extraction time not defined; Schick et al. (2013): soil to solution ratio 1:10, extraction time 60 minutes. In Switzerland only used for lime-free soils, only H_2O-CO_2 data of Swiss LTFEs considered for analysis.

[b] Equation deduced from mean values of STP.

[c] Significant correlation for whole database (all soils or countries), while coefficient stems from only a group of soils or a single country.

[d] Standard deviation (SD) of ratio (coefficient) calculated from ratios of single locations

[e] Equation deduced from mean value of ratios of single locations.

[f] Schick et al. (2013) and Shwiekh et al. (2015) mostly share the same database; r values are generally identical, but while calculation of mean values is based on Shwiekh et al. (2015), some r values are not stated there and r value is therefore added from Schick et al. (2013).

[g] Apparently X and Y are mixed up in regression tables of the publication, equations were adapted according to corresponding regression figure.

Significance levels * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table 3

STP methods and thresholds of the target P fertility classes in fertilizer recommendations of different European countries. Values are default values or mean values of a range of values. The range is given in brackets if different thresholds for different soils, crops or regions are explicitly stated. Adjustments of fertilizer rates deviating from P export due to crop or soil texture, without affecting the general threshold of the fertility class, are possible. Values based on other STP methods than Olsen were converted according to the equations given in Table 2.

Country	Reference	STP method	Threshold of target P fertility class (mg P kg^{-1} soil)[a]	Converted threshold (mg Olsen-P kg^{-1} soil)
Finland[b]	Peltovuori, 1999; Sisällysluettelo 235/2015, 2015	AAAc	6.7 (4.1–10)[c]	37 (25–48)
Belgium (Wallonia)[d]	Genot et al., 2011	AAAc-EDTA	43 (26–66)	17 (10–26)
Switzerland[e]	Richner and Sinaj, 2017	AAAc-EDTA	43 (20–65)	17 (8–26)
Belgium (Flanders)[f]	Jordan-Meille et al., 2012	AL	120	55
Norway	Krogstad et al., 2008	AL	50	26
Sweden[g]	Albertsson, 2008	AL	41	22
Austria	Baumgarten, 2017	CAL	47	26
Germany[h]	VDLUFA, 2018	CAL	31	17
Poland[f]	Jordan-Meille et al., 2012	DL	45	18
Netherlands[d]	de Haan and van Geel, 2013	H_2O	8.4 (6.7–10)[c]	25 (20–30)
Switzerland[e]	Richner and Sinaj, 2017	H_2O-CO_2	1.1 (0.62–1.9)	18 (10–29)
Czech Republic[i]	Sbírka zákonů Česká Republika, 2017	Mehlich 3	81	33
Denmark	Knudsen, 2008	Olsen	20	20
France[d, j]	COMIFER, 2019	Olsen	31 (20–59)	31 (20–59)
Italy[f]	Jordan-Meille et al., 2012	Olsen	10	10
Spain[f]	Jordan-Meille et al., 2012	Olsen	12	12
United Kingdom	DEFRA, 2010	Olsen	12[c]	12[c]

[a] Information given in form of mg P 100 g^{-1} soil or mg P_2O_5 kg^{-1} soil has been transformed to mg P kg^{-1} soil prior to the entry to this overview ($P/P_2O_5 = 0.4364$).

[b] Not a recommendation but upper limits of allowed fertilizer rates for farmers participating in the FAEP (Finnish Agri-Environmental Programme, ca. 90% of farms). No clear range with maintenance fertilization, therefore medium fertility class used for comparison. Extreme differences between crops with partially very high

allowed rates in medium class. Very different values dependent on soil texture and organic matter, given value is a mean value.

[c] Information given in form of mg P l^{-1} soil has been transformed to mg P kg^{-1} soil prior to the entry to this overview assuming an average bulk density of 1.3 kg l^{-1} (Nawara et al., 2017).

[d] Threshold is dependent on crop/pH/region/soil, given value is a mean value.

[e] In Switzerland H_2O-CO_2 and AAAc-EDTA are used, but AAAc-EDTA only for lime-free soils. Different thresholds for different soil textures. Given value is a mean value.

[f] Threshold of medium fertility class, unclear if default fertilization in this class precisely equals export as original recommendation document has not been reviewed.

[g] Recommended fertilizer rates highly differ between crops, independent from expected yield.

[h] Additionally to CAL, some federal states use the DL method.

[i] Given value applies for determination by photometry, values are slightly higher for ICP-OES (86 instead of 81 mg P kg^{-1}).

[j] Additionally to Olsen, the methods Dyer (Dyer, 1894) and Joret-Hébert (Joret and Hébert, 1955) are used.

Table 4

Experimental sites along with responsible institutions and references for further details.

Country	Site/experiment	Institution	Reference
Austria	Fuchsenbigl (FU), Rottenhaus (RT), Zwettl (ZW)	AGES (Austrian Agency for Health and Food Safety)	Lindenthal et al., 2003; Spiegel et al., 2001
	Grabenegg (GR; Alpenvorland), Rutzendorf (RU; Marchfeld)		Spiegel et al., 2018
Belgium	Gembloux (GE)	Walloon Agricultural Research Centre (CRA-W)	Nawara et al., 2017
Denmark	Askov (AS), Borris (BO), Højer (HO), Lundgård (LG), Ødum (OD), Rønhave (RH), Roskilde (RK), Tylstrup (TY)	Aarhus University	Rubæk and Sibbesen, 2000
France	Auzeville (AU; Toulouse)	National Research Institute for Agriculture, Food and Environment (INRAE) Toulouse	Colomb et al., 2007; Nawara et al., 2017
	Mant (MA)	National Research Institute for Agriculture, Food and Environment (INRAE) Bordeaux	Morel et al., 2014; Messiga et al., 2010
	Pierroton (PI)		Denoroy et al., 2012; Nawara et al., 2017
	Tartas (TA)		Morel et al., 2014; Nawara et al., 2017
Germany	Bad Lauchstädt (BA; Static Fertilization Experiment)	UFZ (Helmholtz-Centre for Environmental Research)	Merbach and Schulz, 2012
	Berge (BG; F2-1 and F2-25), Besse (BS; F2-24), Dörnhagen (DO; F2-21), Grebenstein (GS; F2-3 and F2-20), Grimelsheim (GH; F2-30), Haldorf (HD; F2-2 and F2-31), Maden (MD; F2-16), Niedervorschütz (NV; F2-4), Niederzwehren (NZ; F2-36), Zell (ZE; F2-35)	LLH (Landesbetrieb Landwirtschaft Hessen)	Schaumberg and Heyn, 1996
	Biberach (BI), Blaufelden (BL), Emmendingen (EM), Ladenburg (LB), Pfullendorf (PF), Schwäbisch Gmünd (SG), Tuttlingen (TU)	Agricultural Technology Center Augustenberg	Mokry, 1996
	Braunschweig (BR; FV4)	JKI (Julius-Kühn-Institute)	Vogeler et al., 2009
	Freising (Dürnast) (FR; 016, 021 and 022)	Technical University of Munich	von Tucher et al., 2017; von Tucher et al., 2018
	Gülzow (GU)	Research Institute for Agriculture and Fisheries Mecklenburg-Western Pomerania (LFA)	Boelcke, 2007
	Halle (HA)	Martin Luther University Halle-Wittenberg	Gransee and Merbach, 2000
	Rostock (RO)	University of Rostock	Zicker et al., 2018
Sweden	Lanna (LA; 1936 and 1941)	Swedish University of Agricultural Sciences	Simonsson et al., 2018
Switzer-land	Ellighausen (EL), Oensingen (OE), Zurich-Reckenholz (ZR), Ruemlang-Altwi (RA)	Agroscope	Gallet et al., 2003; Hirte et al., 2021
United Kingdom	Rothamsted (RS; Broadbalk Winter Wheat experiment and Exhaustion Land experiment)	Rothamsted Research	Poulton et al., 2013; Johnston and Poulton, 2018
	Saxmundham (SA; Rotation II experiment)		Johnston et al., 2013

Table 5

Overview of the soil properties of the unfertilized treatments (including converted STP values).

Soil parameter	n	Min	Max	Mean	SD	Median
Olsen-P (mg P kg^{-1})	2368	1.0	193.4	22.1	14.9	21.4
Clay (%)	2368	2.8	46.5	23.1	10.7	20.1
C_{org} (%)	2313	0.67	2.7	1.4	0.44	1.2
pH_{CaCl2}	2368	4.5	7.8	6.3	0.66	6.3