Re-evaluation of the yield response to phosphorus fertilization based on meta-analyses of long-term field experiments

Uwe Buczko, Michael van Laak, Bettina Eichler-Löbermann, Wolfgang Gans, Ines Merbach, Kerstin Panten, Edgar Peiter, Thomas Reitz, Heide Spiegel, Sabine von Tucher

Published online: 20 November 2017

Abstract Phosphorus (P) fertilizer recommendations in most European countries are based on plant-available soil P contents and long-term field experiments. Site-specific conditions are often neglected, resulting in excessive P fertilizer applications. P fertilization experiments including relevant site and soil parameters were evaluated in order to analyze the yield response. The database comprises about 2000 datasets from 30 field experiments from Germany and Austria. Statistical evaluations using a classification and regression tree approach, and multiple linear regression analysis indicate that besides plant-available soil P content, soil texture and soil organic matter content have a large influence on the effectiveness of P fertilization. This study methodology can be a basis for modification and specification of existing P fertilization recommendations and thus contribute to mitigate environmental impacts of P fertilization.

Keywords CART · Crop yield · Fertilization · Phosphorus · Plant-available soil phosphorus

INTRODUCTION

Phosphorus (P) is one of the major macronutrients for plant growth and adequate P fertilization is essential to attain optimum yields (Smil 2000). On the other hand, excessive P fertilization is undesirable because P is a scarce, non-renewable resource (Cordell et al. 2009; Vaccari 2009; Schoumans et al. 2015; Mew 2016) and diffuse P losses from excessively fertilized fields are a major cause of eutrophication in surface waters (Correll 1998; Buczko and Kuchenbuch 2007).

In most countries, P fertilizer recommendations are based on the expected nutrient uptake by crops (expected yield × expected P concentration of crop) and the plant-available P content in the soil (Jordan-Meille et al. 2012). The procedure of deducing phosphorus fertilizer recommendations entails three steps (Jordan-Meille et al. 2012): (i) Extraction of plant-available soil P, (ii) calibration of those soil test results, (iii) deducing recommended P fertilizer amounts.

There is no standard definition of “plant-available” P in the soil. Therefore, the term “plant-available” is not defined unambiguously, and for the estimation of plant-available P in the soil, a large variety of extraction methods are in use. In Europe and worldwide, the recommended extraction procedures for the determination of plant-available P differ among countries (Neyroud and Lischer 2003; Jordan-Meille et al. 2012). In Germany, 14 of the 16 federal states base their fertilizer recommendations on the calcium acetate lactate (CAL) extraction method, which employs a solution of calcium lactate, calcium acetate, and acetic acid (Schüller 1969). In two federal states the double lactate (DL) method is used (Riehm 1942). In the calibration step, plant-available P contents are categorized into several classes (in Germany and many other countries five classes), which are interpreted in terms of nutrient supply. These calibrations are mostly based on long-term fertilization trials (Kuchenbuch and Buczko 2011). However, the database used for the calibration step is mostly not accessible in the international literature, and even in countries which use the same extraction procedure, the boundaries of the nutrient availability classes may diverge considerably (Jordan-Meille et al. 2012). This holds true even for various federal states of Germany (Römer 2015).
Various studies have shown that P fertilization recommendations in Germany and several other European countries have been too high in the past several years (Ott and Rechberger 2012; Tóth et al. 2014; Withers et al. 2014), and consequently, the boundaries of the P fertility classes have been too high (VDLUFA 2015). Moreover, besides plant-available soil P contents, other factors have an influence on yield (Kuchenbuch and Buczko 2011), for instance pH value, soil organic carbon content, clay content, weather, and climate parameters. In Germany, the boundaries of the fertility classes (“A” with the lowest, and “E” with the highest contents, whereas the intermediate class “C” is considered optimal for crop growth) are based on yield and soil test data from long-term field experiments, but in general, the calibration procedures are not published. Often, the boundaries are set according to practical considerations and changed with time (Übelhör and Hartwig 2012).

Although in Germany and other countries there is a large number of long-term field experiments dealing with the effects of P fertilization on crop yields (e.g., Baier et al. 2001; Spiegel et al. 2001; Merbach and Schulz 2012), the results of those field fertilization trials have mostly not been compiled or evaluated and analyzed as a whole in the form of a meta-study. In a previous meta-analysis, Kuchenbuch and Buczko (2011) evaluated mainly the results of fertilization trials gained from published, openly accessible sources, whereas large databases remain unpublished at various institutions.

Since in large databases, information about the relationships among the data is often not available prior to analysis, and classification and regression tree approaches (CART, Sonquist and Morgan 1964; Sutton 2005; Strobl et al. 2009) are commonly used in such analyses. CART approaches are non-parametric and do not require any previous assumptions about the distributions or linearity of the variables. Furthermore, they are resistant to outliers and both categorical and numerical predictor variables can be combined. They are relatively easy to use and the interpretation of the resulting trees is straightforward. These methods are applicable in many cases when classical parametric methods are not applicable, for instance in cases with many predictor variables but relatively few datasets (Sonquist and Morgan 1964; Strobl et al. 2009). In agricultural sciences, CART approaches have been used to predict how yield is influenced by soil and management factors (Lapen et al. 2001; Lobell et al. 2005; Zheng et al. 2009; Kuchenbuch and Buczko 2011).

The objectives of this work were to compile a large database of long-term P fertilization experiments from Germany and Austria with special emphasis on data which have until now not been published. A meta-analysis of this data was conducted including statistical methods to evaluate the influence of various site-specific soil and environmental factors on the effectiveness of P fertilization.

MATERIALS AND METHODS

Compilation of database

Data of phosphorus fertilization trials across Germany and Austria were compiled (Fig. 1) (Table 1). All field experiments focused on the effect of P fertilization on yields and are therefore one-factorial fertilization trials with application rates ranging between 10 and 210 kg P ha\(^{-1}\) yea\(^{-1}\), i.e., 30–2000% of P export by crops (calculated from actual crop yields and literature data for P contents of various crop types) (Table 2). Effects of fertilizer application rates on yields were compared by calculating the relative yield increases (\(Y_I\) in %) from the ratio of the yield of the fertilized treatment \(y_f\) and that of the zero fertilization (control) treatment \(y_0\):

\[
y_I = \left(\frac{y_f}{y_0}\right) - 1 \times 100
\]

i.e., \(Y_I\) is the percentage value of the increase in crop yield of the fertilized treatment compared with the corresponding control treatment.

Soil test values and site-specific factors (pH, organic carbon content, and clay content) are summarized in Tables 1 and 2. Note that this parameter list does not encompass all parameters which probably have an influence on the effectiveness of P fertilization on yields. However, in most of the trials, such parameters were not measured or recorded (for instance, sorption capacity, content of Fe- and Al-oxides, P content in subsoil, root density, cation exchange capacity).

Tables 1 and 2 show that the studied soils have rather high soil P contents. Nevertheless, P fertilizer application rates are very high: in 50% of the data, more than 158% of the P was exported by harvested crops (Table 2).

The fertilization trials have mostly been conducted over many years (see Table S1), and the duration of the experiments utilized in the present meta-analysis is in some cases longer than 20 years (Table 1). The most frequent soil types were Luvisols. The crop rotations are dominated by the crops grown most commonly in Germany, i.e., winter wheat \((n = 568)\), winter barley \((n = 305)\), summer barley \((n = 202)\), sugar beet \((n = 200)\), potato \((n = 197)\), and oilseed rape (canola) \((n = 129)\) (see also Fig. 5).

Data analysis

The aim of this study was to evaluate the effectiveness of P fertilization on crop yields for a given soil P content. In a
similar manner to a previous meta-analysis (Kuchenbuch and Buczko 2011), the data of the field trials were analyzed with a classification and regression tree (CART) approach. This methodology is based on splitting the dataset into segments with a distinct factor combination. As in other CART approaches (Strobl et al. 2009), the impact of several predictor variables on a dependent variable is analyzed by successive binary splits. To determine which predictor variable is best to be used for the split and to calculate the corresponding value of the split point for every allowable split on each predictor variable, the within-segment and between-segment sums of squares are calculated. The split (i.e., predictor variable and split point) which yields the most homogeneous binary split in terms of the dependent variable (i.e., with the largest between-segment and smallest within-segment sum of squares) is chosen for the splitting. The result of the analysis is a binary tree diagram. The endpoints of this tree are relatively homogeneous subgroups of the data. The resulting trees are easy to interpret, since the successive binary splits indicate the relative importance of the predictor variables in explaining the dependent variable. However, as with most other statistical methods, the results provide no information about the processes governing the effect of the influencing variables on the dependent variable. Consequently, the results of this procedure should be complemented by expert knowledge, hypotheses, and further statistical methods. Therefore, multiple linear regression analyses were conducted for comparison (Lobell et al. 2005). Both the CART and regression analyses were done using the program SPSS (version 20.0).

For both the CART and regression analyses, the dependent variable was the relative yield increase (YI), and the influencing factors (predictor variables) were plant-
available soil P content (soil test phosphorus, STP), clay content, organic carbon content, pH value, relative P fertilizer application rate, and crop species.

A concern when analyzing time-series data with regression models and regression trees is serial correlation, i.e., the data are auto-correlated in time and therefore not independent. Although the regression coefficients remain unaffected by serial correlation, standard errors may be underestimated (and significances overestimated) when serial correlation occurs (Durbin and Watson 1950; Verbeek 2004). This will lead to the conclusion that the parameter estimates are more precise than they actually are. Since the data used in this study are partly in the form of time-series, we tested for serial correlation using the Durbin–Watson test (Durbin and Watson 1950; Verbeek 2004). This yielded partially Durbin–Watson values \(< 1\), which indicates serial correlation. Consequently, one must be aware that significances of regression tree analysis and

| Site (state) | Duration\(^a\) | \(N\) | \(\text{P(CAL,DL)}\)\(^b\) (mg P 100 g\(^{-1}\) soil), in year of trial establishment | \(\text{pH}\) | \(C_{\text{org}}\) (%) | Clay (%) | Soil type |
|-------------|----------------|------|---------------------------------------------------------------------------------|--------|-----------------|---------|-----------|
| Berge (He)  | 1973–1996      | 69   | 5.4                                                                              | 6.7    | 1.6             | 22      | Luvisol   |
| Besse (He)  | 1986–1996      | 30   | 9.9                                                                              | 6.4    | 1.3             | 25      | Luvisol   |
| Biberach (BW)| 1986–1993      | 24   | 11                                                                               | 5.6    | –               | 9       | Luvisol   |
| Blaufelden (BW) | 1984–1993 | 24   | 4.0                                                                              | 6.3    | –               | 21      | Luvisol   |
| Braunschweig (LS)| 1986–1996 | 109  | 3.4                                                                              | 5.3    | 1.3             | 13      | Cambisol  |
| Dörnhagen (He) | 1984–2008    | 74   | 4.7                                                                              | 6.5    | 1.0             | 15      | Luvisol   |
| Emmendingen (BW)| 1984–1993  | 30   | 8.4                                                                              | 7      | –               | 24      | Luvisol   |
| Freising (Dürrnast) 16 (Ba) | 1978–2014    | 74   | 4.5                                                                              | 6.1    | 1.1             | 24      | Luvisol   |
| Freising (Dürrnast) 021 (Ba) | 1980–2014    | 105  | 6.6                                                                              | 6.2    | 1.1             | 20      | Luvisol   |
| Freising (Dürrnast) 022 (Ba) | 1980–2014    | 102  | 6.9                                                                              | 6.1    | 1.3             | 20      | Luvisol   |
| Fuchshesnbigl (NÖ) | 1976–2003   | 199  | 17.0                                                                             | 7.5    | 1.1             | 18      | Chernozem |
| Grebenstein (He) | 1973–2008    | 99   | 9.3                                                                              | 6.4    | 1.1             | 15      | Luvisol   |
| Grimalsheim (He) | 1997–2003    | 21   | 6.4                                                                              | 6.8    | 1.8             | 24      | Luvisol   |
| Gülozow (MV) | 1998–2014     | 96   | 8.8                                                                              | 6      | 0.7             | 7.3      | Luvisol   |
| Haldorf (He)  | 1973–2008     | 81   | 8.0                                                                              | 6.7    | 1.4             | 10.9     | Luvisol   |
| Halle (SA)   | 1979–2012     | 114  | 6.7                                                                              | 5.8    | 1.5             | 13      | Luvisol   |
| Hohenlosms (He) | 1996–2005    | 70   | 5.3                                                                              | 5.3    | 1.6             | 21      | Cambisol  |
| Ladenburg (BW)| 1984–1993     | 27   | 6.2                                                                              | 6.2    | –               | 21      | Luvisol   |
| Lauchstädt (SA)| 1991–2010    | 20   | 3.3                                                                              | 5.8    | 2.1             | 21      | Chernozem |
| Ludwigslust (Lehse) (MV) | 1995–2004 | 57   | 5.1                                                                              | 6.3    | 0.9             | 9       | Luvisol   |
| Maden (He)   | 1981–1988     | 32   | 9.0                                                                              | 6.1    | 1.3             | 18      | Luvisol   |
| Niedervorschütz (He) | 1974–1985  | 48   | 12                                                                               | 7      | 1.1             | 16      | Luvisol   |
| Niederzerahren (He) | 2007–2008    | 6    | 5.6                                                                              | 6.7    | 1.1             | 13      | no data   |
| Pfüllendorf (BW)| 1984–1993    | 30   | 9.7                                                                              | 6.1    | –               | 21      | Luvisol   |
| Rostock (MV) | 1999–2014     | 28   | 3.5                                                                              | 5.6    | 1.0             | 3       | Cambisol  |
| Rottenhaus (NÖ) | 1976–2003    | 190  | 6.2                                                                              | 6.5    | 1.4             | 30      | Cambisol  |
| Schwäbisch Gmünd (BW) | 1984–1993  | 27   | 11                                                                               | 6.2    | –               | 21      | Luvisol   |
| Sieversen (LS)| 1999–2003     | 36   | 9.0                                                                              | 6.2    | 1.9             | 5.5      | Cambisol  |
| Tuttingen (BW) | 1984–1992     | 24   | 3.1                                                                              | 6.3    | –               | 35      | Luvisol   |
| Zell (He)    | 2006–2008     | 9    | 8.2                                                                              | 6      | 1.8             | 17      | no data   |
| Zwettl (NÖ)  | 1976–2003     | 163  | 7.9                                                                              | 5.4    | 1               | 16      | Cambisol  |

\(^a\) “Duration” here refers to the data utilized for the meta-analysis and does not necessarily coincide with the total duration of the field experiment; for information about the total duration of the field experiments, please refer to Table A1 in the appendix

\(^b\) Average values of the first trial year that was used in our analysis; for the data from MV and SA, the DL extraction procedure was used; for all other the CAL extraction, it was assumed that \(\text{P(CAL)} = \text{P(DL)}\) (Neyroud and Lischer 2003); samples were extracted usually from 0 to 30 cm soil depth
linear regression may be slightly overestimated due to serial correlation.

RESULTS AND DISCUSSION

The relation between STP and YI for all data points (Fig. 2) reveals highest YI for the soil P content class B and lower YI for higher P content classes (for the boundaries of the classes, see Fig. 2). Similarly, the variability of YI is highest for P content class B and decreases towards class E. When YI values are averaged for each of the five P content classes (Table 3), there are statistically significant differences between the P content classes. Whereas the highest average YI by P fertilization was observed for the P content class B, for P content class A, statistically valid numbers cannot be calculated due to the exceedingly low number of data (n = 10). Due to the large variability of YI values observed for all soil P classes, it is difficult to confirm or reject the actual boundaries of soil P classes based on these data alone.

For all soil P classes, the large number of data points with negative YI, i.e., yield depressions, is striking. This is a phenomenon commonly observed in long-term fertilization trials (e.g., Köster and Schachtschabel 1983; Jungk et al. 1993; Römer 2009; Kuchenbuch and Buczko 2011). Since the yield depressions observed here are more or less equal for all soil P content classes (A: 20%, B: 30.6%, C: 29%, D: 30.5%, E: 41% of datasets), and soil P toxicity is rare under field conditions (Zorn et al. 2013; Lambers and Plaxton 2015), the negative YI cannot reasonably be explained directly by the effect of P fertilization. However, indirectly, high levels of plant-available P (as provided by mineral fertilizer) in general reduce root density (Forde and Lorenzo 2001), and the development of mycorrhiza (Mäder et al. 2000; Williams et al. 2017). This could have a

Table 2 Ranges of most important soil and fertilization parameters across all field sites

| Parameter                                     | Min. | Median | Mean  | Max. |
|-----------------------------------------------|------|--------|-------|------|
| Clay content (%)                              | 5.5  | 18.0   | 18.0  | 35.0 |
| Soil organic matter (SOM) (%)                 | 1.2  | 2.0    | 2.1   | 3.6  |
| pH                                            | 4.4  | 6.3    | 6.3   | 7.8  |
| Plant-available P in soil (P-DL or P-CAL) (mg P 100 g⁻¹) | 1.3  | 8.3    | 10.0  | 53.2 |
| P fertilization (kg P ha⁻¹ year⁻¹)             | 9.8  | 43.0   | 60.7  | 209.8|
| Rel. P fertilizer addition [P addition/P export (%)] | 29.5 | 157.8  | 261.3 | 2017 |

* Soil P content of all fertilized plots for all years

Fig. 2 Rel. yield increase (YI) versus soil P content (CAL or DL); fertilizer application rate (“fertilizer amount”) expressed as % of P export by harvested crop; P content classes according to VDLUFA (1997)
negative impact on the uptake of water and other nutrient elements, for instance the micronutrients Zn and Cu, thus reducing the yield of fertilized treatments.

Relative yield increases by P fertilization as a function of soil pH class (Table 3) show highest YI values for pH classes A and B (i.e., acid conditions with low pH values, < 6), and lowest values for class E (high pH values, > 7). This is probably connected with the direct correlation between STP and pH values (Pearson $r = 0.41$). At low pH values ($< 5.5$), P is strongly adsorbed (e.g., by Fe- and Al-Oxides) in soils and therefore less readily plant available (e.g., von Tucher et al. 2016). Additionally, soil pH influences the availability of other essential plant nutrients and soil microorganisms and might therefore cause yield effects not investigated in the evaluated phosphorus experiments. There is no clear relation between clay content and YI (Fig. 3). On average, YI is highest for the clay content class of 12–17%.

In line with these findings, the interpretation of the effect of soil clay content on plant availability of soil P is not straightforward: in general, the mobility of nutrient ions (especially in the vicinity of roots) is lower in clay-rich soils because the effective diffusion coefficient decreases with increasing clay content, mainly due to sorption on clay surfaces (Jungk and Claassen 1986; Hinsinger et al. 2009). Consequently, the mobility of nutrient ions is reduced in clay-rich soils. In contrast to most nutrients which occur as cations, the negatively charged phosphate anion is predominantly adsorbed to surfaces of Fe-, Mn-, and Al-oxides. These usually constitute only a minor part of the clay fraction, compared with clay minerals (Jungk and Claassen 1986).

YI increases with SOM content, and highest YI values are observed for SOM contents of 2.5–3% (Table 3). However, for SOM > 3%, YI is again significantly lower (but the number of data in that group is lower than in the other groups). In general, P availability is directly correlated with SOM contents, because adsorption of P is reduced by organic anions such as citrate or malate which compete with phosphate anions for adsorption sites at Fe and Al oxide surfaces (e.g., Hunt et al. 2007; Gerke 2015). This may explain the higher effect of P fertilization with higher SOM contents observed for our data. Moreover, SOM contents are correlated with clay contents (not shown here in detail). However, the lower YI for the highest SOM class is not entirely clear. One possible explanation is, that at high SOM contents the release of available P from organic P compounds is more important than for lower SOM contents.

The relation between P fertilization rate and YI is evaluated here in terms of relative rates, i.e., P input divided by the P export by the harvested crop (Fig. 4).

### Table 3

| P content class | A | B | C | D | E |
|-----------------|---|---|---|---|---|
| Mean YI         | 3.46 | 6.53 | 4.30 | 3.61 | 0.70 |
| N               | 10 | 268 | 903 | 573 | 256 |
| Significance $^a$ | (abc) | a | b | b | c |
| pH class $^b$    | A | B | C | D | E |
| Mean YI         | 7.40 | 4.71 | 2.52 | 2.66 | 1.29 |
| N               | 275 | 849 | 423 | 167 | 296 |
| Significance $^a$ | a | b | c | bc | c |
| SOM class (%) $^c$ | ≤ 1.5 | > 1.5–2 | > 2–2.5 | > 2.5–3 | > 3 |
| Mean YI         | 2.26 | 2.60 | 5.24 | 8.10 | 3.86 |
| N               | 96 | 847 | 527 | 234 | 119 |
| Significance $^a$ | ab | a | b | c | ab |
| Fertilizer type | Superphosphate | Triple superphosphate | Hyperphosphate | Thomas phosphate | Others |
| Mean YI         | 5.10 | 2.36 | 1.31 | 5.06 | 4.28 |
| N               | 839 | 632 | 119 | 304 | 68 |
| Significance $^a$ | a | b | b | a | ab |

$^a$ Small letters denote statistical significance of differences between groups (Tukey HSD post hoc test, $p < 0.05$)

$^b$ According to VDLUFA (2000); the corresponding actual pH values depend on soil texture and SOM. For SOM < 4%, the optimum class C corresponds for sandy soil texture to pH values 5.4–5.8. This range gradually increases with clay content up to 6.4–7.2 for a clayey loam to clay soil

$^c$ Arbitrary SOM classes, since existing SOM classes (e.g., VDLUFA 2000) do not distinguish for SOM < 4%
Although the YI values are on average highest for relative rates of 100–150%, the differences among the groups are mostly not significant, and conspicuously, the YI values are relatively low for high rates of P input (> 200% of exported P). This applies also when only data for soil P class B are considered (not shown here in detail).
Such a lack of stringent relation between P fertilizer amount and yield increase has been reported in previous studies (e.g., Jungk et al. 1993) and suggests that in most cases the pool of plant-available P in the soil is sufficient for high crop yields, and the applied fertilizer P is used mainly to maintain or even enhance this soil P pool. This is in accordance with the philosophy of “maintenance fertilization” (Jordan-Meille et al. 2012), although recently this approach has been questioned (Withers et al. 2014). Additionally, more important than the applied amount of fertilizer is the P content of the control plot. In cases where the soil P content of the unfertilized control is above 9 mg P/100 g, the fertilized plots only show an average yield increase of 1.1%, irrespective of the total available P (soil P + fertilizer P) in the treatment plot. A low correlation between P amount supplied versus plant yields (Pearson $r = -0.10$) may also indicate the active mobilization of soil P resources by plants by root exudates, mycorrhiza and fine roots (Eichler-Lößermann et al. 2007; Requejo and Eichler-Lößermann 2014), which is not routinely measured and is not a part of current fertilization recommendations.

When evaluating the effect of P fertilizer type on YI, there are statistically significant differences between treatments fertilized with Superphosphate and Thomas phosphate on one hand, and Triple superphosphate and Hyperphosphate on the other hand (Table 3). The lower effectiveness of Hyperphosphate (i.e., finely ground rock phosphate) in non-acid soils compared with Superphosphate is expected and in line with previous studies (e.g., Spiegel et al. 2001; von Tucher 2013). However, one would expect that Superphosphate and Triple superphosphate are similarly available, since both are produced by reaction of rock phosphate with inorganic acids (sulfuric acid and phosphoric acid). In contrast to Triple superphosphate, Superphosphate contains remnants of sulfate, which is a macronutrient. This could be an explanation for the higher effectiveness of Superphosphate. The relatively high effectiveness of Thomas phosphate could possibly be caused by the high content of Ca and micronutrients (e.g., Fe, Mn, Zn), and the alkaline soil reaction induced by this fertilizer.

A comparison of the effectiveness of P fertilization among the six most common crops (Fig. 5) shows overall highest yield increase for summer barley, and lowest increases for winter wheat. When only soils with low soil phosphorus content (fertility class B) are considered, sugar beet shows the strongest response (12.6% mean YI) to fertilizer application, winter wheat (3.2% mean YI) and canola (oilseed rape) (2.7% mean YI) tend to respond less (not shown here in detail). In the previous section (Table 3 and Figs. 2, 3, 4, 5), the YI was evaluated as a function of several separate factors. All these factors are combined as independent variables in an analysis by means of a classification and regression tree approach (Fig. 6).

The first split was set by the CART algorithm for the independent variable plant-available soil P content (STP), at a value of 3.34 mg P 100 g$^{-1}$ soil. This indicates that
plant-available soil P content is the most important variable determining yield increase by P fertilization.

If the STP of the control is above 3.3 mg P 100 g⁻¹, average YI is only 2.75% (compared to 10.4%). This result supports the latest VDLUFA recommendation (VDLUFA 2015) to reduce the lower boundary of the P content class “C” to 3.0 mg P 100 g⁻¹.

The second split is implemented according to crop species and again STP, i.e., these independent variables explain for each of the branches the largest part of the variance in YI. The blue end segments indicate the mean YI for the combination of parameters according to the respective branch of the decision tree. This can be demonstrated exemplarily for a dataset from Rottenhaus (Austria) dating from the year 1981 (Spiegel et al. 2001). The plant-available soil P content is 4.5 mg P 100 g⁻¹ soil, i.e., at the lower margin of P content class C (VDLUFA 1997). Clay content is 30% and pH 5.98. The

---

Table 4 Results of multiple linear regression analysis of rel. yield increase as a function of pH, P(CAL,DL), SOM content, clay content, and relative fertilizer amount; all data combined and separately for fertilizer types

| Parameter                        | Standardized coefficient (β) |
|----------------------------------|-----------------------------|
|                                  | All data | Superphosphate | TSP | Thomas phosphate |
| pH                               | -0.111*** | 0.044 (ns)     | -0.162*** | 0.112 (ns)     |
| P(CAL,DL)                        | -0.152*** | -0.374***     | -0.078 (ns) | -0.206**     |
| SOM                              | 0.097***  | 0.023 (ns)     | 0.17**   | 0.213**     |
| Clay content                     | -0.033 (ns) | -0.183***     | -0.072 (ns) | -0.228**     |
| Relative fertilizer amount       | -0.021 (ns) | 0.16**       | 0.055 (ns) | -0.171*     |

Significance levels: * p < 0.05; ** p < 0.01; *** p < 0.001; ns: p > 0.05 (not significant)
fertilizer application rate of 172 kg P ha\(^{-1}\) year\(^{-1}\) in the form of Superphosphate corresponds to 642\% of P export by the crop (26.8 kg P ha\(^{-1}\)). Nevertheless, the fertilizer application rate is, according to the CART analysis, not among the most important variables explaining the observed yield increase. For this dataset, the predicted YI is 5.3\% (Fig. 6), whereas measured YI is 4.5\%. Similarly, multiple linear regression analysis suggests that plant-available P content, pH value, and SOM content are the most significant variables; however, with large differences among different fertilizer types (Table 4). This is in line with the results from a meta-analysis of P fertilizer experiments in Finland (Valkama et al. 2009).

**CONCLUSIONS**

This meta-analysis of a database of long-term field experiments of P fertilization covering various regions of Germany and Austria including about 2000 datasets from 30 field sites revealed that yield increase due to the effect of fresh P application is determined mainly by plant-available P in the soil, pH value, SOM, type of fertilizer, and crop type, whereas the exact amount of P fertilizer has less importance. The database will be expanded in the near future, and additional parameters will be included in the analysis, most notably soil type, precipitation, and air temperature. In a next step, the results will be utilized to refine the current P fertilizer recommendations. Although only data from Germany and Austria are utilized in the present analysis, this approach can be extended to other countries worldwide, and the results gained in the analyses can be transferred to other environmental conditions and countries. This could contribute to more precise P fertilization recommendations, less application of P fertilizer, and diminished negative environmental impacts of P fertilization.

**Acknowledgements** This work was conducted within the framework of the InnoSoilPhos project (BMFB BONARES program, Grant No. 031A558A). We want to thank Dr. Ines Bull (Mecklenburg-Vorpommern Research Centre for Agriculture and Fisheries), Dr. Martin Rex (Agricultural Research Station Kamperhof), Dr. Markus Mokry (Agricultural Technology Center Augustenberg), and Dr. Johannes Heyn/Dierk Koch Landesbetrieb Landwirtschaft Hessen for providing data of long-term field fertilization trials.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

**REFERENCES**

Baier, J., V. Baierová, Z. Bartošová, and D. Ledvinková. 2001. Yields nutrient intake and soil fertilizing in 40 years fertilizer trials. Archives of Agronomy and Soil Science 46: 313–337.

Boelcke, B. 2007. P/K-Düngung im Wintergetreideanbau. Getreide magazin 2007: 170–177. (in German).

Buczko, U., and R.O. Kuchenbuch. 2007. Phosphorus indices as risk assessment tools in the U.S.A. and Europe—A review. Journal of Plant Nutrition Soil Science 170: 445–460.

Cordell, D., J.O. Drangert, and S. White. 2009. The story of phosphorus: Global food security and food for thought. Global Environmental Change 19: 292–305.

Correll, D. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. Journal of Environmental Quality 27: 261–266.

Durbin, J., and G.S. Watson. 1950. Testing for serial correlation in least squares regression. I. Biometrika 37: 409–428.

Eichler-Loßmann, B., S. Köhne, and D. Köppen. 2007. Effect of organic, inorganic and combined organic and inorganic P fertilization on plant P uptake and soil P pools. Journal of Plant Nutrition Soil Science 107: 623–628.

Eichler-Loßmann, B., S. Köhne, B. Kowalski, and E. Schnug. 2008. Effect of catch cropping on phosphorus bioavailability in comparison to organic and inorganic fertilization. Journal of Plant Nutrition 31: 659–676.

Forde, B., and H. Lorenzo. 2001. The nutritional control of root development. Plant and Soil 232: 51–68.

Gerke, J. 2015. The acquisition of phosphate by higher plants: Effect of carboxylate release by the roots. A critical review. Journal of Plant Nutrition Soil Science 178: 351–364.

Gransee, A., and W. Merbach. 2000. Phosphorus dynamics in a long term P fertilization trial on Luvis Phaeozem at Halle. Journal of Plant Nutrition Soil Science 163: 353–357.

Hinsinger, P., A.G. Bengough, D. Vetterlein, and I.M. Young. 2009. Rhizosphere: Biophysics, biogeochemistry and ecological relevance. Plant and Soil 321: 117–152.

Hunt, J.F., T. Ohno, Z. He, C.W. Honeycutt, and D.B. Dail. 2007. Inhibition of phosphorus sorption to goethite, gibbsite, and kaolinite by fresh and decomposed organic matter. Biology and Fertility of Soils 44: 277–288.

Jordan-Meille, L., G.H. Rubæk, P.A.I. Ehlert, V. Genot, G. Hofman, K. Goulding, J. Becknagel, G. Provolo, et al. 2012. An overview of fertilizer-P recommendations in Europe: Soil testing, calibration and fertilizer recommendations. Soil Use and Management 28: 419–435.

Jungk, A., and N. Claassen. 1986. Availability of phosphate and potassium as the result of interaction between root and soil in the rhizosphere. Journal of Plant Nutrition Soil Science 149: 411–427.

Jungk, A., N. Claassen, V. Schulz, and J. Wendt. 1993. Pflanzenernährung durch Phosphatdüngung erzielbaren Mehrertrag und dem Phosphatgehalt im Boden. Journal of Plant Nutrition Soil Science 156: 397–406. (in German).

Köster, W., and P. Schachtstabel. 1983. Beziehung zwischen dem durch Phosphatdüngung erzielbaren Mehrertrag und dem Phosphatgehalt im Boden. Journal of Plant Nutrition Soil Science 146: 539–542. (in German).

Krey, T., N. Vassilev, C. Baum, and B. Eichler-Loßmann. 2013. Effects of long-term phosphorus application and plant growth promoting rhizobacteria on maize phosphorus nutrition under field conditions. European Journal of Soil Biology 55: 124–130.

Kuchenbuch, R.O., and U. Buczko. 2011. Re-visiting potassium- and phosphate-fertilizer responses in field experiments and soil-test
interpretations by means of data mining. *Journal of Plant Nutrition Soil Science* 174: 171–185.

Lammers, H., and W.C. Plaxton. 2015. Phosphorus: Back to the roots. *Annual Plant Reviews* 48: 3–22.

Lapen, D.R., G.C. Topp, E.G. Gregorich, H.N. Hayhoe, and W.E. Curnoe. 2001. Divisive field-scale associations between corn yields, management, and soil information. *Soil Tillage Research* 58: 193–206.

Lindenthal, T., H. Spiegel, M. Mazorek, J. Heß, B. Freyer, and A. Köchl. 2003. Results of three long-term P-field experiments in Austria 2nd Report: Effects of different types and quantities of P-fertiliser on P-uptake and P-balances. *Die Bodenkultur* 54: 11–21.

Lobell, D.B., J.I. Ortiz-Monasterio, G.P. Asner, R.L. Naylor, and Merbach, I., and E. Schulz. 2012. Long-term fertilization effects on Mew, M.C. 2016. Phosphate rock costs, prices and resources Schüller, H. 1969. Die CAL-Methode, eine neue Methode zur S60 Ambio 2018, 47(Suppl. 1):S50–S61

Lapen, D.R., G.C. Topp, E.G. Gregorich, H.N. Hayhoe, and W.E. Curnoe. 2001. Divisive field-scale associations between corn yields, management, and soil information. *Soil Tillage Research* 58: 193–206.

Lindenthal, T., H. Spiegel, M. Mazorek, J. Heß, B. Freyer, and A. Köchl. 2003. Results of three long-term P-field experiments in Austria 2nd Report: Effects of different types and quantities of P-fertiliser on P-uptake and P-balances. *Die Bodenkultur* 54: 11–21.

Lobell, D.B., J.I. Ortiz-Monasterio, G.P. Asner, R.L. Naylor, and W.P. Falcon. 2005. Combining field surveys, remote sensing, and regression trees to understand yield variations in an irrigated wheat landscape. *Agronomy Journal* 97: 241–249.

Mäder, P., S. Edenhofer, T. Boller, A. Wiemken, and U. Niggli. 2000. Arbuscular mycorrhizae in a long-term field trial comparing low-input (organic, biological) and high-input (conventional) farming systems in a crop rotation. *Biology and Fertility of Soils* 31: 150–156.

Merbach, I., and E. Schulz. 2012. Long-term fertilization effects on crop yields, soil fertility and sustainability in the Static Fertilization Experiment Bad Lauchstädt under climatic conditions 2001–2010. *Archives of Agronomy and Soil Science* 59: 1041–1057.

Mew, M.C. 2016. Phosphate rock costs, prices and resources interaction. *Science of the Total Environment* 542: 1008–1012.

Mokry M. 1996. P-Düngungsversuche—Baden-Württemberg. VDLUFA-Schriftenreihe 42: 4–10. (in German).

Neyroud, J.A., and P. Lischer. 2003. Do different methods used to estimate soil P availability across Europe give comparable results? *Journal of Plant Nutrition and Soil Science* 166: 422–431.

Ott, C., and H. Rechberger. 2012. The European phosphorus balance. *Resources, Conservation and Recycling* 60: 159–172.

Requejo, M., and B. Eichler-Löbermann. 2014. Organic and inorganic phosphorus forms in soil as affected by long-term application of organic amendments. *Nutrient Cycling in Agroecosystems* 100: 245–255.

Rex, M. 1999. Wirkung der Phosphatdüngung bei Ausbringung im Herbst oder Frühjahr. VDLUFA-Schriftenreihe 52: 251–254. (in German).

Riehm, H. 1942. Bestimmung der laktathaltigen Phosphorsäure in karbonathaltigen Böden. *Die Phosphorsäure* 1: 167–178. (in German).

Römer, W. 2009. Ansätze für eine effizientere Nutzung des Phosphors auf der Basis experimenteller Befunde. *Berichte über Landwirtschaft* 87: 5–30. (in German).

Römer, W. 2015. Die Versorgung der deutschen Ackerböden mit Phosphat und die Herausforderungen der Zukunft [The phosphate supply of arable land in Germany and the challenges of future]. *Bodenschutz* 4: 125–130. (in German).

Schaumberg, G., and J. Heyn. 1996. Prüfung optimaler Phosphat-Versorgungsbereiche/Hessen. VDLUFA-Schriftenreihe 42: 11–19. (in German).

Schoumans, O.F., E. Bouraoui, C. Kabbe, O. Oenema, and K.C. van Schoumans, O.F., F. Bouraoui, C. Kabbe, O. Oenema, and K.C. van Kc. von Tucher, S. 2013. Einfluss von Boden und P-Düngern auf die P-Aufnahme einiger mono- und dikotyler Pflanzenarten. *Alpenländisches Expertenforum* 18: 5–8. (in German).

Sonquist, J.A., and J.N. Morgan. 1964. The detection of interaction effects—A report on a computer program for the selection of optimal combinations of explanatory variables. Monograph No. 35, Survey Research Center, Institute for Social Research, University of Michigan, Ann Arbor.

Spiegel, H., T. Lindenthal, M. Mazorek, A. Ploner, B. Freyer, and A. Köchl. 2001. Ergebnisse von drei 40jährigen P-Dauerversuchen in Österreich: 1. Mitteilung: Auswirkungen ausgewählter P-Düngerformen und -mengen auf den Ertrag und die PCAL/ DL-Gehalte im Boden. *Die Bodenkultur* 52: 3–17. (in German).

Strobl, C., J. Malley, and G. Tutz. 2009. An introduction to recursive partitioning. Technical Report Number 55, 2009. Department of Statistics, University of Munich. http://www.stat.uni-muenchen.de.

Sutton, C.D. 2005. Classification and regression trees, bagging, and boosting. In *Handbook of statistics*, vol. 24.

Töth, G., R.A. Guicharnaud, B. Töth, and T. Hermann. 2014. Phosphorus levels in croplands of the European Union with implications for P fertilizer use. *European Journal of Agronomy* 55: 42–52.

Uebelhoer, W., and H. Hartwig. 2012. Phosphorklassen im Wandel der Zeit. *Landinfo* 1: 33–36. (in German).

Vaccari, D.A. 2009. Phosphorus: A looming crisis. *Scientific American* 300: 54–59.

Valkama, E., R. Uusitalo, K. Ylivainio, P. Virkajarvi, and E. Turtola. 2009. Phosphorus fertilization: A meta-analysis of 80 years of research in Finland. *Agriculture, Ecosystems & Environment* 130: 75–85.

VDLUFA. 1997. VDLUFA Standpunkt: Phosphorungung nach Bodenuntersuchung und Pflanzenbedarf, Eigenverlag Darmstadt. (in German).

VDLUFA. 2000. Bestimmung des Kalkbedarfs von Acker- und Grünlandböden. Standpunkt des Verbands Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten. (in German).

VDLUFA. 2015. Phosphorungung nach Bodenuntersuchung Anpassung der Richtwerte für die Gehaltsklassen ist geboten und notwendig. Positionspapier des Verbands Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten. (in German).

Verbeek, M. 2004. A guide to modern econometrics, 2nd ed. Chichester: Wiley.

Vogeler, I., J. Rogusik, U. Funder, K. Panten, and E. Schmug. 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. *Soil and Tillage Research* 103: 137–143.

von Tucher, S. 2013. Einfluss von Boden und P-Düngerform auf die P-Aufnahme einiger mono- und dikotyler Pflanzenarten. *Alpenländisches Expertenforum* 18: 5–8. (in German).

von Tucher, S., D. Hördnell, and U. Schmidhalter. 2016. Wirkung differenzierter P-Düngung und Kalkung auf Ertrag und P-Aufnahme von Winterweizen, Wintergerste und Beta-Ruiben im Langzeitexperiment. Kongressband 2016 VDLUFA-Schriftenreihe 72. (in German).

Williams, A., L. Manoharan, N.P. Rosenstock, P.A. Olsson, and K. Hedlund. 2017. Long-term agricultural fertilization alters arbuscular mycorrhizal fungal community composition and barley (Hordeum vulgare) mycorrhizal carbon and phosphorus exchange. *New Phytologist* 213: 874–885.

Withers, P.J.A., R. Sylvester-Bradley, D.L. Jones, J.R. Healey, and P.J. Talboys. 2014. Feed the crop not the soil: Rethinking phosphorus management in the food chain. *Environmental Science and Technology* 48: 6523–6530.

Zheng, H., L. Chen, X. Han, X. Zhao, and Y. Ma. 2009. Classification and regression tree (CART) for analysis of soybean yield variability among fields in Northeast China: The importance of
phosphorus application rates under drought conditions. Agriculture, Ecosystems & Environment 132: 98–105.
Zorn, W., G. Marks, H. Heß, and W. Bergmann. 2013. Handbuch zur visuellen Diagnose von Ernährungsstörungen bei Kulturpflanzen, 2nd ed. Berlin: Springer. (in German).

AUTHOR BIOGRAPHIES

Uwe Buczko is a senior scientist at the Department of Landscape Ecology and Site Evaluation at the University of Rostock. He has been working for about 10 years on various aspects of Phosphorus in the landscape, among others the description and quantification of diffuse P losses and meta-analyses of long-term P fertilizer experiments.
Address: Department of Landscape Ecology and Site Evaluation, University of Rostock, 18059 Rostock, Germany.
e-mail: uwe.buczko@uni-rostock.de

Michael van Laak is a doctoral candidate at the chair of Landscape Ecology and Site Evaluation at the University of Rostock. He is working in WP 2.3 of the InnoSoilPhos project about meta-analyses of long-term phosphorus fertilizer experiments.
Address: Department of Landscape Ecology and Site Evaluation, University of Rostock, 18059 Rostock, Germany.
e-mail: michael.laak@uni-rostock.de

Bettina Eichler-Loëberman is a senior researcher working mainly in plant nutrition and soil science. She currently focuses on the nutrient availability of recycled phosphorus resources undertaking pot and field experiments as well as on the influence of energy crops on soil physical parameters and water infiltration.
Address: Institute for Crop and Soil Science, Julius Kühn Institute, Federal Research Centre for Cultivated Plants, Bundesallee 50, 38116 Brunswick, Germany.
e-mail: kerstin.panten@julius-kuehn.de

Edgar Peiter is a professor of Plant Nutrition at the Martin Luther University Halle-Wittenberg, Germany. His research interests include the physiological functions of mineral nutrients in plants. He manages the Halle long-term field experiments, in which effects of differential fertilization regimes are studied.
Address: Plant Nutrition Laboratory, Institute of Agricultural and Nutritional Sciences, Martin Luther University Halle-Wittenberg, 06099 Halle (Saale), Germany.
e-mail: edgar.peiter@landw.uni-halle.de

Thomas Reitz is a postdoc at the Helmholtz-Centre of Environmental Research. His research focusses on the impacts of global change, including aspects of climate change as well as land use intensification, on soil nutrient cycling in terrestrial ecosystems. His particular research focus lies on the role of soil microorganisms in plant nutrition by releasing nutrients (N, P, K) from organic matter or non-available nutrient pools.
Address: Helmholtz-Centre for Environmental Research – UFZ, Theodor-Lieser-Str. 4, 06120 Halle (Saale), Germany.
e-mail: thomas.reitz@ufz.de

Heide Spiegel is a senior scientist at AGES, Austria, Habilitation to “Docent for Soil Ecology” at the University of Natural Resources and Life Sciences (BOKU Vienna), working on monitoring the effects of different soil management on soil properties related to nutrient (especially P) and organic matter cycling; soil contamination (acidification, enrichment with selected elements). Scientific management of long-term field experiments.
Address: Austrian Agency for Health and Food Safety – AGES, Spargelfeldstraße 191, 1220 Vienna, Austria.
e-mail: adelheid.spiegel@ages.at

Sabine von Tucher is a senior scientist for plant nutrition at the Chair of Plant Nutrition of the Technical University of Munich with a research focus on the efficiency of nutrients, mainly phosphorus, sulfur, and nitrogen in the plant–soil–environment system. She has more than 25 years research experience in the role of phosphorus in plant growth, in soil P dynamics, and in the effectiveness of different organic and mineral P fertilizers including P recycling products. She is responsible for the long-term P fertilizer experiments of the institute.
Address: Emil-Ramann-Straße 2, 85354 Freising, Germany.
e-mail: tucher@wzw.tum.de

© The Author(s) 2018. This article is an open access publication www.kva.se/en