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RESEARCH ARTICLE

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Decrease in soil test phosphorus levels under omitted phosphorus fertilizer application

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Abstract

Many European cropped soils have high soil test P (STP) values in the top soil because of P accumulation over many years of fertilizer application. This should allow to save P fertilizer applications for some years without STP values decreasing to a level that might negatively impact crop yield. However, the way STP develops under omitted P fertilizer application is not well understood. We examined STP development under omitted P fertilizer application for timeframes between 7 and 46 years on 96 unfertilized treatments (P0 treatments) of 43 European long-term P field experiments, using five different STP methods. For comparability, values obtained by different STP methods were converted to Olsen-P concentrations. We fitted exponential decay curves to Olsen-P data of each P0 treatment defined by initial Olsen-P values (*Olsen-P$_i$*), rates of decrease (k) and asymptotes (A), reflecting minimum obtainable STP. Subsequently, we analysed whether the variables most commonly recorded in experiments, are sufficient to explain the variation in model parameters, these variables being P export, clay content, C_{org} and pH as well as average annual temperature and precipitation. We found that out of our predictor variables, soil clay content, precipitation and temperature were showing the most prominent effects on the parameters *Olsen-P$_i$*, A or k. However, the amount of variation explained by the considered variables was too low to potentially facilitate a prediction of STP decrease, and various P0 treatments showed no clear Olsen-P decrease or unexpectedly high asymptotes. This hints at a strong influence of the P sorption capacity of the soil with often high potential for replenishment from less available P pools. In connection with P introduction from the subsoil or possibly from surrounding plots, the extension of

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timeframes of omitted P fertilizer application without reaching critical STP values for crop production, might be explainable. Corresponding effects could not be analysed because of lack of data for most P0 treatments, calling for the additional determination of, for example, the maximum P sorption capacity, total P and subsoil P in future experiments.

KEYWORDS
European long-term field experiments, exponential decline, legacy P, Olsen-P, residual P

1 | INTRODUCTION

Most fertilizer recommendation schemes are based on a principle of build-up and maintenance, where soil phosphorus (P) status is built up to reach a target range for optimum crop production, which then is maintained by P fertilizer application equal to P export (Jordan-Meille et al., 2012). However, excessive phosphorus (P) fertilizer application in Europe, often related to intensive husbandry, resulted in many areas with overly high soil P status (Sattari et al., 2012). Corresponding risks of the eutrophication of surface waters as well as fluctuating prices of P fertilizers have led to a rising interest in effects of reduced or fully omitted P fertilizer application to mine legacy P instead (Nair et al., 2020; Tyson et al., 2020; von Arb et al., 2021; Withers et al., 2014). The reduction of P input even has become a target of European Union-wide agricultural policy and regulation (Green Deal, Panagos et al., 2022).

The effects of varying phosphorus fertilizer application rates have been the subject of some of the oldest long-term field experiments. The first experiments were started over a century ago, like the Rothamsted Exhaustion Land experiment (Johnston & Poulton, 2018) and the Static Fertilization Experiment in Bad Lauchstädt (Rathke et al., 2002). The use of long-term field experiments with regard to P is not surprising, considering that sufficient P supply to plants only partly depends on recent fertilizer applications but also on the availability of native soil P or previously applied (residual) P in the soil (Syers et al., 2008).

Soil P is distributed between organic and inorganic pools of varying availability, which show complex interactions. Availability depends on processes of precipitation and dissolution as well as adsorption and desorption (e.g. on clay particles, carbonates and Al- or Fe-(hydr)oxides) for transfer of inorganic P between the solid phase and the soil solution. In addition, there is biological immobilization or mineralization, transferring P between the organic and inorganic pools (Frossard et al., 2000). Larger changes of plant availability usually take place slowly over the span of several years (Gatiboni et al., 2021; Johnston et al., 2016; Syers et al., 2008).

The availability of P to crops is estimated by tests using different extraction methods. The resulting soil test P (STP) values vary across methods because of different extraction mechanisms and operational conditions (extraction time, ratio of mass of soil to volume of extraction solution) and therefore different ability to access the different P pools, mostly focussing on inorganic P (e.g. Nawara et al., 2017; Steinfurth et al., 2021).

When long-term fertilizer experiments are established, various P fertilizer rates may be chosen, which are meant to either increase STP (P input > P export) to find values above which yield will no longer increase, maintain STP (P input = P export) or decrease STP (P input < P export). While many experiments have treatments with P fertilizer rates below P export, which will lead to STP decrease, the absolute as well as relative (in relation to P export) rates will vary, reducing comparability. However, most long-term field experiments on P fertilizer application include a treatment without any P fertilizer application (P0 treatment) either for studying effects of long-term P omission itself or as a reference for the effects of different fertilizer types or application rates. The P0 treatments are ideal for investigating how STP decreases with time when the soil is used for plant production without adding more fertilizer (or manure) P and for comparison between treatments of different experiments. A key point of interest in the P0 treatments is to identify for a given soil the STP threshold at which the yield potential can no longer be obtained (the crop yield starts to decrease in comparison to P-fertilized treatments, e.g. falling below 90% or 95% of yields of fertilized treatments). These thresholds are regarded as critical STP values. Above these critical STP values, yields tend to be relatively stable, apart from omnipresent fluctuations based on temperature and precipitation (Nawara et al., 2017; Steinfurth et al., 2022). Yield decrease can be expected if STP decreases below those critical values, which can, however, also depend on the crops cultivated (Eichler-Löbermann et al., 2021; Nawara et al., 2017). This is leading to the frequent use of critical STP values for the definition of fertilizer recommendations (Jordan-Meille et al., 2012; Steinfurth et al., 2022). A common approach for investigating the effects of omitting P fertilizer application is therefore modelling decreases in STP.

There are many studies relating the STP decrease in the P0 treatment to P export (Appelhans et al., 2020; Chen et al., 2022; Messiga et al., 2010), using P export as a variable explaining the pace of STP decrease. Other studies describe the time course of STP decrease as either linear (Ciampitti et al., 2011) or exponential decay functions with (Johnston et al., 2016) or without (Dodd et al., 2012; Schulte et al., 2010) asymptotes of minimum obtainable STP values. These minimum STP values are levels at which no further STP decrease occurs, even though there is P export without any P fertilizer input; a possible explanation being an equilibrium between P export and replenishment of extractable P by less available P pools (Gatiboni et al., 2021).

Soil properties, such as clay or soil organic matter content have been shown to influence STP decrease (Appelhans et al., 2020; Johnston et al., 2016). A high clay content can lead to a higher P sorption capacity (Gérard, 2016), which is often associated with higher contents of Al- and Fe-(hydr)oxides and corresponding P adsorption (Eriksson et al., 2015). Amorphous Al- and Fe-(hydr)oxides strongly influence the P sorption capacity of soils, high contents being able to fix high amounts of P, leading to high total P values while actual availability is low (van Doorn et al., 2023). Soil organic matter content, which is closely related to C_{org}, can exert complex effects on P availability. Promotion of P desorption from soil sorption sites is possible owing to competition with decomposition products of organic matter, but also increase in sorption through metal-chelate linkages (Debicka et al., 2016). Furthermore, high contents of soil organic matter increase the potential for P mineralization (Debicka et al., 2016; Frossard et al., 2000).

There are additional soil and climate variables which may influence P availability as well as STP decrease. Soil pH is affecting adsorption and desorption processes of P as well as P precipitation. At low and high pH values, P is adsorbed mainly by Al- and Fe-(hydr)oxides, while at intermediate pH values it is rather adsorbed by clay minerals (Devau et al., 2009). In addition, P might precipitate with Ca at high pH values (Gustafsson et al., 2012). Temperature and soil moisture (driven by precipitation) affect soil P dynamics, for example, by increased microbial activity under conditions of sufficient moisture and high temperatures and, via P availability, influence general plant growth, and thereby, P uptake and export (Mackay & Barber, 1984, 1985; Sun et al., 2018). In addition to P in the usually sampled soil layer (most often equivalent to the ploughing depth), subsoil P can be an additional source of P for crops (Merbach et al., 2011).

While some of these variables are commonly recorded in long-term field experiments (soil clay content, pH, C_{org}, P export, temperature and precipitation), others are rarely measured (e.g. content of Al- and Fe-(hydr)oxides or subsoil P). In addition, different patterns may occur depending on the STP method, since different methods show varying response to soil characteristics, especially soil pH (Steinfurth et al., 2021).

Research on STP decrease covering varying STP methods as well as many different soils is sparse. Therefore, our objectives were to (i) describe the time course of STP decrease in the P0 treatments of different experiments; (ii) identify those commonly measured variables which affect STP decrease and (iii) evaluate if these variables are sufficient to explain the variability in STP decrease patterns and to facilitate a prediction of STP development under omitted P fertilizer application.

We built a data base of 96 P0 treatments of 43 European long-term P field experiments located in seven European countries using five different STP methods. For comparability, values derived by different STP methods were converted to Olsen-P. Data of individual P0 treatments were used to fit exponential decay curves defined by the initial Olsen-P value, the rate of Olsen-P decrease and an asymptote of minimum obtainable Olsen-P (model type with best fits). Subsequently, these parameters were examined for their dependence on P export, soil properties (clay content, C_{org} and pH) and climatic conditions (temperature and precipitation) as well as patterns connected to the original STP method.

2 | MATERIAL AND METHODS

2.1 | Data collection and pre-processing

2.1.1 | The experiments

We used datasets from 96 treatments without P fertilizer application (P0 treatments) of 43 long-term field experiments on arable land located in seven European countries (Table 1, Figure 1). Data were collected between 1966 and 2023 and were provided by corresponding team members responsible for the individual experiments.

Next to varying P input, some of the experiments offered additional variables, for example, straw incorporation versus removal or different lime treatments. For these experiments, there were several P0 treatments which we examined separately (named A, B, C, etc.). In case of replicated plots (often three to five), mean STP values were used.

Pre-conditions for the inclusion of the P0 treatments were the availability of at least 4 years of soil sampling and

TABLE 1 Experimental sites along with responsible institutions and references for further details. An overview of some properties of the P0 treatments can be found in (Table S1). Abbreviations of locations refer to designations in Figure 1. Table modified after Steinfurth et al. (2022).

Country	Location/experiment	Institution	STP method	References
Austria	Fuchsenbigl (FU; 5 P0 treatments), Rottenhaus (RT; 5 P0 treatments), Zwettl (ZW; 4 P0 treatments)	AGES (Austrian Agency for Health and Food Safety)	CAL	Lindenthal et al. (2003), Spiegel et al. (2001)
	Grabenegg (GR; Alpenvorland; 2 P0 treatments), Rutzendorf (RU; Marchfeld; 2 P0 treatments)		CAL	Spiegel et al. (2018)
Denmark	Askov (AS), Borris (BO), Højer (HO), Lundgård (LG), Ødum (OD), Rønhave (RH), Roskilde (RK), Tylstrup (TY)	Aarhus University	Olsen	Sibbesen et al. (2000)
France	Mant (MA)	National Research Institute for Agriculture, Food and Environment (INRAE), research centre of Bordeaux	Olsen	Morel et al. (2014), Messiga et al. (2010)
	Tartas (TA)		Olsen	Morel et al. (2014), Nawara et al. (2017)
Germany	Bad Lauchstädt (BA; Static Fertilization Experiment, 4 P0 treatments)	UFZ (Helmholtz-Centre for Environmental Research)	DL	Merbach and Schulz (2012), Rathke et al. (2002)
	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)	LLH (Landesbetrieb Landwirtschaft Hessen)	CAL	Schaumberg and Heyn (1996)
	Braunschweig (BR; FV4)	JKI (Julius Kühn Institute)	CAL	Vogeler et al. (2009)
	Freising (Dürnast) (FR; 016: 3 P0 treatments, 021: 8 P0 treatments and 022: 8 P0 treatments)	Technical University of Munich	CAL	von Tucher et al. (2017), von Tucher et al. (2018)
	Gülzow (GU; 3 P0 treatments)	Research Institute for Agriculture and Fisheries Mecklenburg-Western Pomerania (LFA)	DL	Bull (2021)
	Halle (HA; 2 P0 treatments)	Martin Luther University Halle-Wittenberg	CAL, DL	Gransee and Merbach (2000)
	Rostock (RO)	University of Rostock	DL	Zicker et al. (2018)
Sweden	Lanna (LA; R3-1001-1936: 4 P0 treatments and R3-1001-1941: 4 P0 treatments)	Swedish University of Agricultural Sciences	AL	Simonsson et al. (2018); https://glten.org/experiments/382; https://glten.org/experiments/384
Switzerland	Ellighausen (EL), Oensingen (OE), Zürich-Reckenholz (ZR), Rümlang-Altwi (RA)	Agroscope	H_2O–CO_2	Gallet et al. (2003), Hirte et al. (2021)
United Kingdom	Rothamsted (RS; Broadbalk Winter Wheat experiment: 2 P0 treatments and Exhaustion Land experiment: 5 P0 treatments)	Rothamsted Research	Olsen	Glendining and Poulton (2023), Johnston and Poulton (2018), Johnston et al. (2016), Poulton et al. (2013)
	Saxmundham (SA; Rotation II experiment; 8 P0 treatments)			Johnston et al. (2013), Johnston et al. (2016)

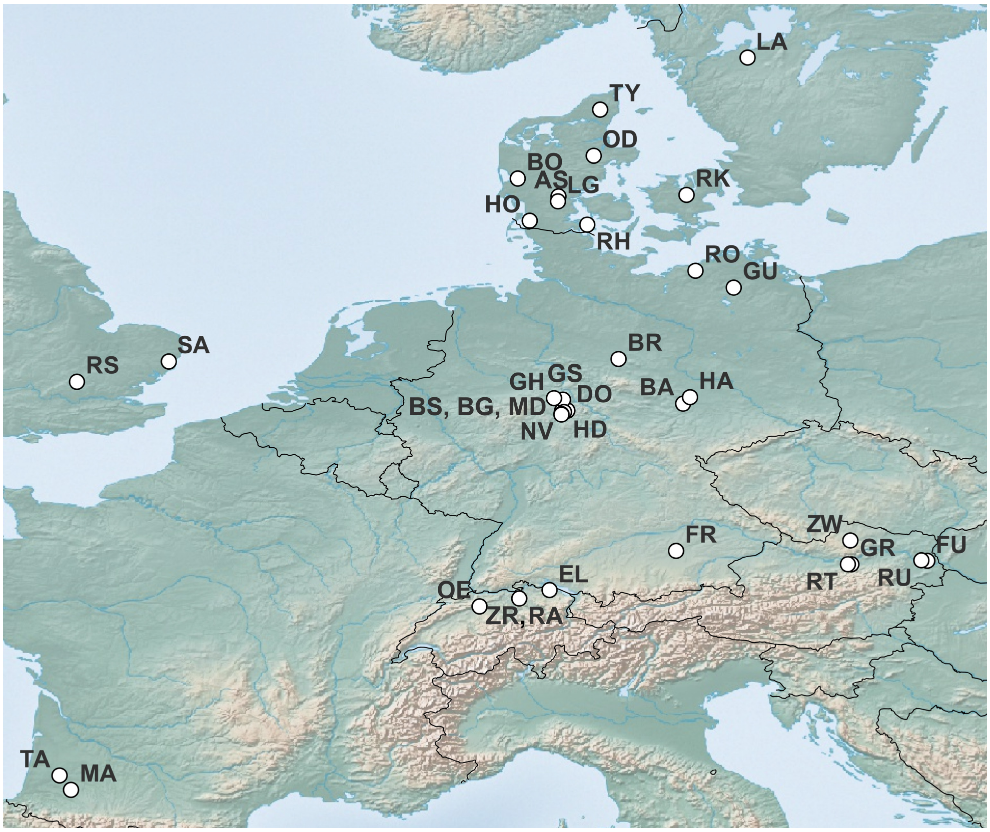

FIGURE 1 Locations of the field experiments included in the analysis. Abbreviations refer to locations as given in Table 1; Map: Natural Earth (a); Natural Earth (b), processed in QGIS (QGIS.org, 2021). AS, Askov; BA, Bad Lauchstädt; BG, Berge; BO, Borris; BR, Braunschweig; BS, Besse; DO, Dörnhagen; EL, Ellighausen; FR, Freising; FU, Fuchsenbigl; GH, Grimelsheim; GR, Grabenegg; GS, Grebenstein; GU, Gülzow; HA, Halle; HD, Haldorf; HO, Højer; LA, Lanna; LG, Lundgård; MA, Mant; MD, Maden; NV, Niedervorschütz; OD, Ødum; OE, Oensingen; RA, Rümlang-Altwi; RH, Rønhave; RK, Roskilde; RO, Rostock; RS, Rothamsted; RT, Rottenhaus; RU, Rutzendorf; SA, Saxmundham; TA, Tartas; TY, Tylstrup; ZR, Zürich-Reckenholz; ZW, Zwettl.

associated STP data as well as data on soil pH, clay content, C_{org} and P export (mostly measured, in some cases estimated based on crop yield). Other variables (e.g. soil Al- and Fe-(hydr)oxide content, subsoil STP, total P) were usually not measured, and therefore, not included in the analyses. Potential effects of changing soil management, crop rotations or varieties within the P0 treatments were not investigated because of a lack of information. For some very old experiments (start of the experiment before 1960), STP data were not available for the whole length of the experiment; in these cases, STP decrease was examined starting from the first year of STP data available to us.

The P0 treatments covered a large range of crops (various cereals, root crops, oil seeds, grass leys, etc.) and different soil properties with soil pH_{CaCl2} values ranging from 4.4 to 7.8, clay contents from 2.8% to 46.5%, and C_{org} contents from 0.67% to 2.7%. Plot sizes ranged between 15 m^2 and 1590 m^2 (see Table S1). Depth of soil sampling in the individual experiments mostly depended on the depth of the plough layer and ranged between 0.2 and 0.3 m. Other nutrients (N, K, etc.) were added through fertilizer application or were considered to already be present in non-limiting amounts at the corresponding sites. Except for the French ones, the experiments were usually not irrigated.

2.1.2 | Alignment of STP and pH values

The use of data from different experiments and countries involved differences also in the choice of the STP method. Of the 96 P0 treatments, eight used P extraction by Ammonium-Lactate (AL), 49 by Calcium-Acetate-Lactate (CAL), 10 by Double-Lactate (DL), four by carbon dioxide-saturated water (H_2O–CO_2) and 25 by the Olsen method (for references see Table 2). For comparison of STP results based on different extraction methods, all STP values were converted into Olsen-P values (Olsen et al., 1954). The Olsen method was chosen as baseline STP method because of its frequent and widespread international use (Jordan-Meille et al., 2012). The STP methods used in the experiments included in this study and selected equations

TABLE 2 Equations used for conversion of STP values obtained by various methods to Olsen-P (Olsen et al., 1954). Table modified after Steinfurth et al. (2022).

Method	Equation	Underlying soils	Quality	References	Used for
AL (Egnér et al., 1960)	$(12.7 + 0.60 \times \text{AL-P}^{0.5} + 0.23 \times \text{Clay}(\%)^{0.5} - 1.99 \times \text{pH}_{H2O})^2$	82 Swedish soil samples	$R^2 = .94$	Otabbong et al. (2009)	Swedish data
CAL (Schüller, 1969)	$0.56 \times \text{CAL-P}$	60 German soil samples	$r^a = .81^{**}$	Shwiekh et al. (2015)[b]	German and Austrian data from loam and clay soils
	$0.71 \times \text{CAL-P}$	6 German loamy sand, sand-loess and loess soils; pH_{CaCl2}: 5.1–6.1	$SD^c = 0.19$, $r^c = .84^*$	von Vetter et al. (1977)[d]	German and Austrian data from loamy sand soils and silt soils with average $\text{pH}_{CaCl2} < 6.0$
	$0.50 \times \text{CAL-P}$	191 German loess soils, pH_{CaCl2}: 4.9–7.7	$r = .86^{**}$	Schachtschabel (1973)[b]	German and Austrian data from silt soils with average $\text{pH}_{CaCl2} > 6.0$
DL (Riehm, 1943)	$0.52 \times \text{DL-P}$	6 German loamy sand, sand-loess and loess soils; pH_{CaCl2}: 5.1–6.1	$SD^c = 0.15$; $r^a = .63^*$	von Vetter et al. (1977)[d]	German data from loamy sand soils and silt soils with average $\text{pH}_{CaCl2} < 6$
	$0.42 \times \text{DL-P}$	191 German loess soils, pH_{CaCl2}: 4.9–7.7	$r = .81^{**}$	Schachtschabel (1973)[b]	German data from silt soils with average $\text{pH}_{CaCl2} > 6$
H_2O–CO_2 (Dirks & Scheffer, 1930)	$15.8 \times \text{P}_{H2O-CO2}$	135 soil samples from 12 European countries	NA	Neyroud and Lischer (2003)[b]	Swiss data

Note: Significance levels $^*p < .05$; $^{**}p < .01$.

[a]Significant correlation for whole database (all soils or countries), while coefficient is based only on the described underlying soils.

[b]Equation deduced from mean values of STP.

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

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

for conversion are listed in Table 2. Main criteria for the selection of equations were similarities in soil properties between the soils used here and the soils used for establishing the equation. In addition, equations with very high intercepts were avoided, since these are not able to generate low Olsen-P values (Steinfurth et al., 2021).

When extraction mechanisms between methods differ strongly (e.g. acid extraction methods compared with alkaline ones; Steinfurth et al., 2021), soil pH can influence results and might be included in conversion equations. Examples for the comparability between values generated by different STP methods and the effect of the inclusion of pH in a conversion equation can be found in (Figures S1 and S2).

For the joint analysis of pH influences, pH values measured in a soil suspension of water instead of a solution of $CaCl_2$, were converted according to Equation (1), based on data 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):

$$\text{pH}_{CaCl2} = \text{pH}_{H2O} - 0.59 \text{ (SD: 0.10)} \tag{1}$$

This equation matches with the difference between the two pH methods given in standard soil science textbooks (0.6 (±0.2) pH units; Blume et al., 2016).

2.2 | Investigating the time-course of STP decrease

For each individual P0 treatment, we attempted to fit a three-parameter (Olsen-P_i, A and k) model of Olsen-P development over time based on Johnston et al. (2016; Equation 2). This form of equation was used since an exponential decay curve with an asymptote clearly resulted in the best fit for a large proportion of the treatments. If model fitting was not possible or a negative A value was generated, modelling was repeated without the parameter A.

$$\text{Olsen-P}_t = \left(\text{Olsen-P}_i - A\right) \times \exp\left(-k \times t\right) + A \tag{2}$$

where Olsen-P_t is the Olsen-P value [$mg\,kg^{-1}$] in year t, *Olsen-P_i* is the initial (first year of STP data) Olsen-P value [$mg\,kg^{-1}$], k is the coefficient defining the rate of decrease in Olsen-P per unit of time [yr^{-1}], t is the number of years elapsed since the first observed year [yr], A is the asymptote [$mg\,kg^{-1}$], which is the lowest obtainable Olsen-P value.

The value of Olsen-P_i could have a large influence on the curve progression, if the curve is forced through the exact point of the first measured value. To reduce the impact of random effects related to sampling and analysis as well as effects caused by crop and year, Olsen-P_i was instead estimated through the model similar to the approach in Dodd et al. (2012). Values strongly deviating from the overall trend were removed in case of Cook's distance >1 (outliers; less than 1% of the observations). Regressions were conducted in R (Version 4.2.3; R Core Team, 2023) using the nls (Nonlinear Least Squares) function.

Correlations between the parameters Olsen-P_i, k and A for the P0 treatments with significant A values ($n=52$) as well as P0 treatments with k values used for further analyses ($n=26$, significant, positive k values based on regressions including all three parameters Olsen-P_i, k and A) were investigated using the Spearman-method. Correlations were not tested for all P0 treatments with significant Olsen-P_i ($n=96$), owing to missing A values for some P0 treatments.

2.3 | Identification of variables which explain the variability of STP decrease

2.3.1 | Considered predictor variables

We hypothesized that Olsen-P decrease differs between the P0 treatments and that this is related to soil properties, climatic conditions and P export. Therefore, the parameters Olsen-P_i, k and A of the individual trials were examined with regard to influences of different predictor variables: average soil clay content [%], soil pH, C_{org} [%], mean annual temperature [°C], annual precipitation [$mm\,yr^{-1}$] and P export from the P0 treatment [$kg\,ha^{-1}\,yr^{-1}$].

Average values of the predictor variables for the time period covered by STP measurements were used to match the multi-year nature of the coefficients and simulate constant conditions to make results potentially applicable for the estimation of future Olsen-P decrease based on current conditions or average conditions of previous years. Long-term average values of precipitation and temperature of the experimental sites were gathered from the corresponding literature or data provided by persons associated with the experiments. If such data were not available (some German experiments), average values were calculated using the grids of the DWD Climate Data Center (CDC) of the corresponding years (DWD CDC (a); DWD CDC (b)).

Prior to analysis, the predictor variables were standardized (centred and scaled to mean 0 and standard deviation 1).

We checked for correlations within the predictor variables (Figure 2), using the Spearman method. Since correlations between predictor variables were moderate at best, none of them were excluded from further analyses. In addition, we conducted a Principal Component Analyses (PCA) for the predictor variables with grouping by the original STP method (Figure 3), using the function 'prcomp' in R (Version 4.2.3; R Core Team, 2023), to check for clusters in the variables caused by, for example, many experiments using a given method being implemented by the same institution with similar set ups on similar soils, which could lead to an overestimation of variable effects. Next to possible method-related effects, the narrow cluster formed by the P0 treatments using the AL method (Figure 3; P0 treatments of the Lanna experiments (Lanna

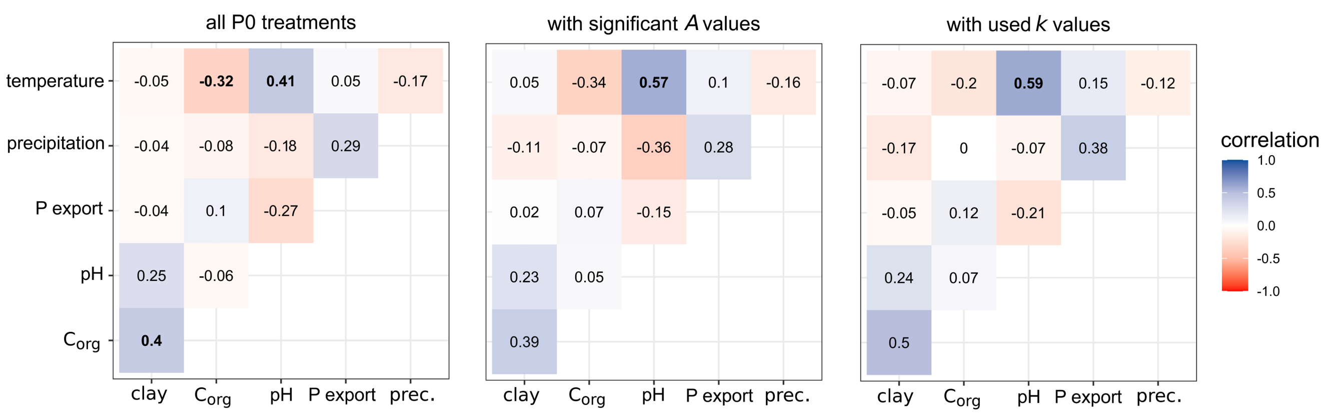

FIGURE 2 Correlations between the predictor variables for all P0 treatments ($n=96$, equals the P0 treatments with significant Olsen-P_i values), with significant A values ($n=52$) as well as the P0 treatments with k values used for further analyses ($n=26$, significant, positive k values based on regressions including all three parameters Olsen-P_i, k and A).

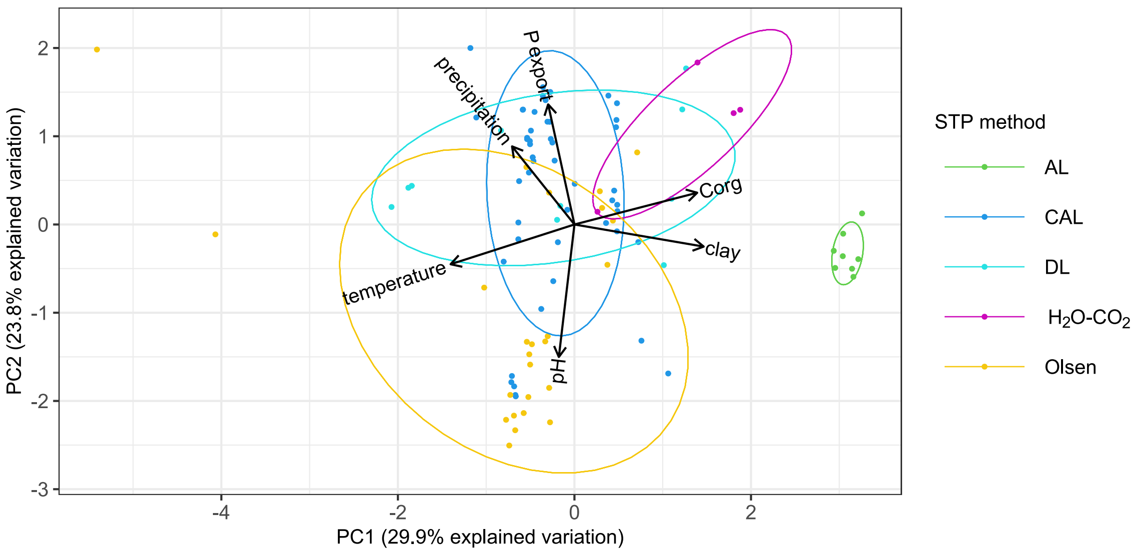

FIGURE 3 Principal Component Analysis (PCA) of the standardized predictor variables with grouping by original STP method, $n = 96$.

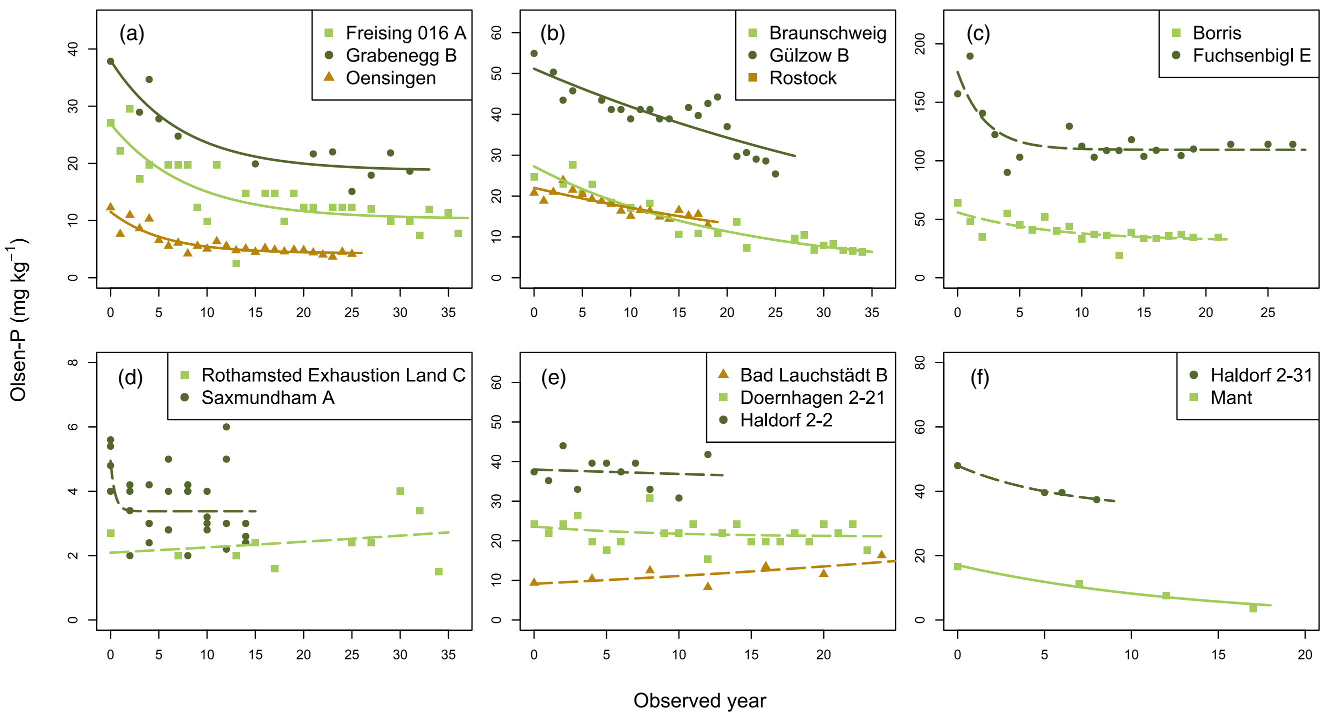

FIGURE 4 Examples of Olsen-P regressions of individual treatments. Dashed lines indicate a non-significant ($p > .05$) k value. (a) Shows different examples of regressions resulting in significant k and A values. (b) Shows examples of regressions with significant k but non-significant or removed A; Braunschweig includes a non-significant A value; for Gülzow B, a model fit was only possible after A was removed from the regression equation; for Rostock, A was removed from the equation after being negative. (c) Shows examples of regressions with an apparent decrease in Olsen-P (but non-significant k) and a significant and very high A. (d) Shows examples of regressions in which values are very low and asymptotes might have already been reached. (e) Shows further examples of P0 treatments in which the asymptote presumably has already been reached, but at higher levels compared to Rothamsted Exhaustion Land C. (f) Shows examples of regressions based on a low amount of data with (Mant) and without (Haldorf 2–31) significant k values.

1936 and Lanna 1941)) was a main reason to introduce the original STP method as a random effect.

2.3.2 | Included parameter values and modelling

Only significant ($p < .05$) Olsen-P_i, k and A values were used for model fitting (see Table S1). For comparability, only those significant k values were used, which were positive (Olsen-P decrease over time) and based on regressions including all three parameters Olsen-P_i, k and A.

Mixed effect models for Olsen-P_i, A and k were fit using the function 'lmer' of the R-package 'lme4' (Bates et al., 2015) and subjected to stepwise selection (backward) using the function 'step' of the R-package 'lmerTest' (Kuznetsova et al., 2017). This resulted in models in the form of Equation (3):

$$y = (\text{Intercept} \mid \text{original STP method}) + a \times V1 + b \times V2 \quad (3)$$

where y is either Olsen-P_i, A or k, the original STP method is applied as a random effect to the intercept, V (1, 2) are the standardized predictor variables determined by stepwise selection and a and b are the coefficients corresponding to the variables.

As a supplementary analysis of possible effects of the differing original STP methods, Olsen-P_i, A and k were tested for differences between original STP methods using the Kruskal–Wallis test followed by Dunn's test with Bonferroni correction (because of partial lack of equality of variances).

3 | RESULTS

3.1 | Regressions of Olsen-P values of individual P0 treatments

Of 96 regressions, 64 included all of the parameters (Olsen-P_i, k and A), while for 32 P0 treatments, regression was conducted without the parameter A since a fit including A could not be achieved or produced a negative A value (see Table S1, column 'Comment').

We identified different types of regression outcome, which are shown in Figure 4.

There were several P0 treatments showing a very clear decrease in Olsen-P in combination with a significant asymptote (A) (Figure 4a). In particular, the four Swiss P0 treatments (e.g. Oensingen, Figure 4a) showed very well-defined curves with low asymptotes. Other cases showed a significant decrease rate (k), while A was not significant (Figure 4b, Braunschweig) or removed from the regression (Figure 4b, Gülzow B and Rostock). Often, the significant A values were very high (e.g. Figure 4c, Borris: 32 mg Olsen-P kg^{-1}; Fuchsenbigl E: 109 mg Olsen-P kg^{-1}). In addition, there were cases without apparent changes in Olsen-P, where the asymptotes might already have been reached, but asymptotes broadly varied in magnitude (Figure 4d: very low; Figure 4e: varying levels). The P0 treatment of Mant had a low number of Olsen-P measurements, but still produced a significant k value. This was not the case for Haldorf 2–31 (Figure 4f), where a decrease in Olsen-P was apparent but the according rate was not significant.

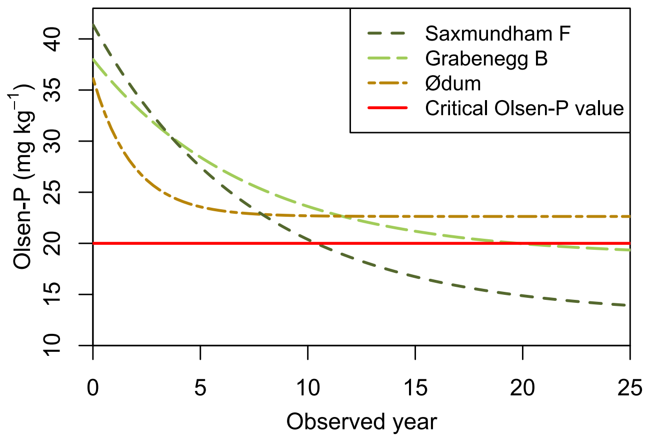

FIGURE 5 Examples of P0 treatments with similar Olsen-P_i values but different numbers of years needed to reach a given critical Olsen-P value (20 mg Olsen-P kg^{-1}, based on the lower limit of the target range of a Danish fertilizer recommendation (Knudsen, 2008)). For Saxmundham F the critical value was reached after 11 years, for Grabenegg B after 20 years; for Ødum the asymptote lies above the critical value.

Examples of different curves in relation to the time needed to reach a given critical Olsen-P value are presented in Figure 5. P0 treatments with similar Olsen-P_i values needed widely different numbers of years to reach a given critical Olsen-P value depending on their respective k and A values.

All of the 96 regressions resulted in a significant Olsen-P_i value. A was significant for 52 P0 treatments, 36 showed a significant k value. For 25 P0 treatments, all three parameters were significant (Table 3; an average curve of the treatments with all parameters being significant ($n = 25$) can be found in Figure S3). Of the 52 significant A values, 50 lay below their corresponding Olsen-P_i value (i.e. Olsen-P decrease over time), in two cases (Tylstrup and Niedervorschütz F2-4), A was higher than Olsen-P_i (i.e. Olsen-P increase over time).

One P0 treatment (Besse F2-24) had a significant, but negative k value (i.e. Olsen-P increase over time). Significant values of the parameters Olsen-P_i, A and k as well as k values used for further analysis (significant,

TABLE 3 Numbers of P0 treatments with specific regression outcomes. For the categorization into 'Olsen-P decrease' or 'Olsen-P increase', only the fitted curve shape was considered, not the significance of the parameters.

	Total number of P0 treatments = P0 treatments with significant Olsen-P_i	With significant *A* value	With significant *k* value	With significant Olsen-P_i, *k* and *A* value
All types of curves	96	52	36	25
Parameters Olsen-P_i, *k* and *A*, Olsen-P decrease	62	50	26	25
Parameters Olsen-P_i, *k* and *A*, Olsen-P increase	2	2	0	0
Parameters Olsen-P_i and *k*, Olsen-P decrease	24	0	9	0
Parameters Olsen-P_i and *k*, Olsen-P increase	8	0	1	0

positive *k* values based on regressions including all three parameters Olsen-P_i, *k* and *A*) are presented in Figure 6.

Significant values ranged from 2 to 176 mg Olsen-P kg^{-1} for Olsen-P_i and 3 to 109 mg Olsen-P kg^{-1} for *A*. Significant *k* values ranged from −0.036 yr^{-1} (slight Olsen-P increase) to 1.19 yr^{-1} (fast Olsen-P decrease) with the lowest value being the only negative one (Besse 2–24), showing a significant increase rate of Olsen-P instead of a decrease. The highest *k* value of 1.19 yr^{-1} (Zwettl B) was about double that of the second highest *k* value (Ødum: 0.533 yr^{-1}).

There was a strong positive correlation between Olsen-P_i and *A* values for P0 treatments with significant *A* values as well as the P0 treatments with *k* values used for further analyses (see Figure S4).

3.2 | Mixed effects models

3.2.1 | Influences on *Olsen-P_i* values

Stepwise selection led to the inclusion of the predictor variables clay and precipitation in the model, both showing a similarly strong effect (Table 4, decreasing Olsen-P_i values at increasing values of clay content and precipitation). Nonetheless, the fixed effects explained only a small proportion of variation (marginal R^2 = .20) compared with the random effects which led to an improvement to .52 (conditional R^2). This strong effect of the original STP method is further illustrated by partially significant differences between Olsen-P_i values grouped by the original STP method (Figure 7). Olsen-P_i values of P0 treatments originally using the CAL method were significantly higher than those of P0 treatments using the Olsen or H_2O–CO_2 method, with values of the H_2O–CO_2 group also showing the narrowest range.

The Root Mean Square Error (22.6 mg Olsen-P kg^{-1}) lies only slightly below the standard deviation of the Olsen-P_i values (27.3 mg Olsen-P kg^{-1}), implying a low level of accuracy of prediction.

3.2.2 | Influences on *A* values

For significant *A* values, stepwise selection also led to the inclusion of the predictor variables clay and precipitation in the model, with clay exerting a stronger effect than precipitation (Table 5, decreasing Olsen-P_i values at increasing values of clay content and precipitation). Similar to the modelling of Olsen-P_i, the fixed effects explained only a small proportion of variation (marginal R^2 = .36) compared with the random effects which led to an improvement to .83 (conditional R^2). This strong effect of the original STP method is illustrated by significant

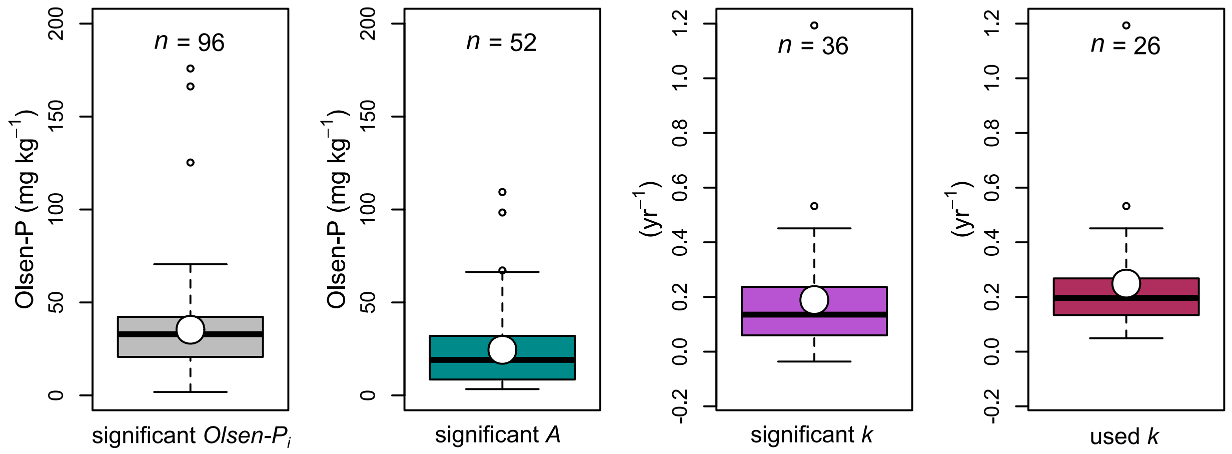

FIGURE 6 Number and range of significant ($p < .05$) values of Olsen-P_i, A and k as well as k values used for further analysis (significant, positive k values based on regressions including all three parameters Olsen-P_i, k and A).

TABLE 4 Result of stepwise model selection for significant Olsen-P_i values (mean: 35.3 mg Olsen-P kg^{-1}, standard deviation: 27.3 mg Olsen-P kg^{-1}). The predictor variables were standardized (centred and scaled to mean 0 and standard deviation 1). Original mean (and standard deviation) of clay: 21.5% (10.0%) and of precipitation: 695 mm yr^{-1} (148 mm yr^{-1}). $n = 96$; significance levels *$p < .05$; **$p < .01$; ***$p < .001$. For a full list of average values and standard deviations of the predictor variables, see Table S2.

Dependent variable: Olsen-P_i (mg Olsen-P kg^{-1})		
Random effects		
	Standard deviation	
Original STP method (5 groups)	18.92	
Residual	23.39	
Fixed effects		
	Estimate	p-value
Intercept	33.4	.0457*
Clay (standardized)	−12.0	.0032**
Precipitation (standardized)	−10.1	.0010**
Root Mean Square Error		22.6
Marginal R^2		.20
Conditional R^2		.52

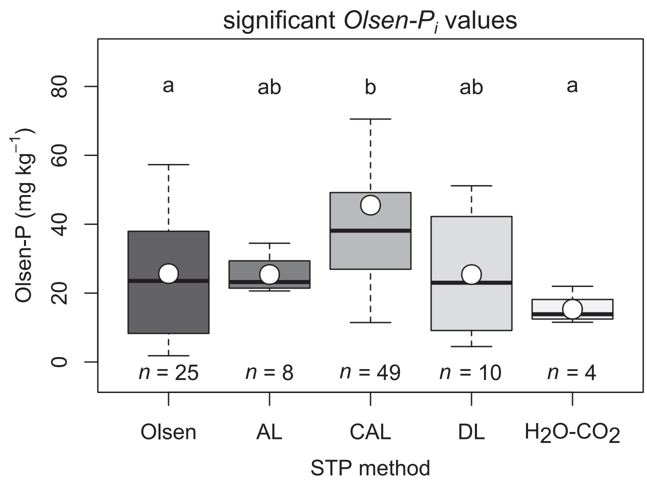

FIGURE 7 Significant Olsen-P_i values sorted by original STP method. White circles mark the mean values. The letters above the plots mark significant ($p < .05$) differences between methods.

differences between A values of P0 treatments using different methods (Figure 8). A values of P0 treatments originally using the CAL method were significantly higher than those of P0 treatments using the Olsen, AL or H_2O–CO_2 method, and also showed a larger range of values.

3.2.3 | Influences on k values

Stepwise selection led to the inclusion of the predictor variables temperature and precipitation in the model, with temperature showing a stronger effect and a higher level of significance (Table 6, decreasing k values (slower Olsen-P decrease) at increasing values of temperature and precipitation). The fixed effects resulted in a marginal R^2 of .40, under inclusion of the random effects a conditional R^2 of .81 was reached. There were no significant differences between k values grouped by the original STP method (see Figure S5), but the number of values per group was low, partially leading to very low variance within a group.

4 | DISCUSSION

4.1 | Regressions of Olsen-P values of individual P0 treatments

4.1.1 | The *Olsen-P_i* values

Next to the P content of the parent material, the values of Olsen-P_i (as well as total P values and P distribution

TABLE 5 Result of stepwise model selection for significant *A* values (mean: 24.5 mg Olsen-P kg^{-1}, standard deviation: 22.3 mg Olsen-P kg^{-1}). The predictor variables were standardized (centred and scaled to mean 0 and standard deviation 1). Original mean (and standard deviation) of clay: 23.1% (11.3%) and of precipitation: 683 mm yr^{-1} (135 mm yr^{-1}). $n = 52$; significance levels $*p < .05$; $**p < .01$; $***p < .001$. For a full list of average values and standard deviations of the predictor variables, see Table S2.

Dependent variable: *A* (mg Olsen-P kg^{-1})		
Random effects		
	Standard deviation	
Original STP method (5 groups)	24.7	
Residual	14.9	
Fixed effects		
	Estimate	*p*-value
Intercept	22.6	.1678
Clay (standardized)	−17.4	.0003***
Precipitation (standardized)	−13.3	.0001***
Root Mean Square Error		13.9
Marginal R^2		.36
Conditional R^2		.83

TABLE 6 Result of stepwise model selection for significant, positive *k* values based on regressions including all three parameters Olsen-P_i, *k* and *A* (mean: 0.249 yr^{-1}, standard deviation: 0.220 yr^{-1}). The predictor variables were standardized (centred and scaled to mean 0 and standard deviation 1). Original mean (and standard deviation) of temperature: 8.4°C (0.9°C) and of precipitation: 708 mm yr^{-1} (157 mm yr^{-1}). $n = 26$; significance levels $*p < .05$; $**p < .01$; $***p < .001$. For a full list of average values and standard deviations of the predictor variables, see Table S2.

Dependent variable: *k* (yr^{-1})		
Random effects		
	Standard deviation	
Original STP method (5 groups)	0.230	
Residual	0.159	
Fixed effects		
	Estimate	*p*-value
Intercept	0.215	.206
Temperature (standardized)	−0.191	.0001***
Precipitation (standardized)	−0.143	.0244*
Root Mean Square Error		0.139
Marginal R^2		.40
Conditional R^2		.81

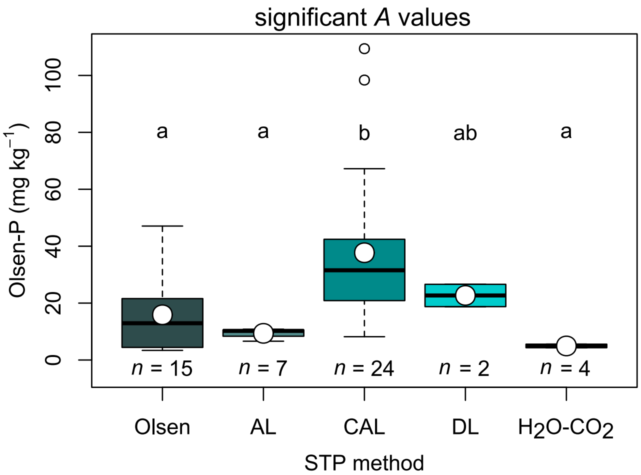

FIGURE 8 Significant *A* values sorted by original STP method. White circles mark the mean values. The letters above the plots mark significant ($p < .05$) differences between methods.

between pools of different availability) can be expected to be highly dependent on extent, form and duration of P fertilizer application before fertilizer application was omitted (residual P; Appelhans et al., 2024; Johnston & Poulton, 2019), the maximum P sorption capacity of the soil (as a function of amorphous Al- and Fe-(hydr)oxides) (van Doorn et al., 2023), and for very old experiments, the number of unfertilized years elapsed before the first STP measurements (see Figure S6). Unfortunately, the fertilizer application history before the start of the experiments was often unclear or there was only very limited information. In addition, subsoil P and P introduction from surrounding plots might play a role (see Section 4.1.2.). Since most experiments did not offer data on Al- and Fe-(hydr)oxides, corresponding connections could not be investigated, but it should be mentioned that there might be some correlation to soil clay contents (Eriksson et al., 2015).

Owing to changing fertilizer application practices since the start of the first experiments, an effect of the first year without fertilizer application and interaction with elapsed time seemed possible but could not be proven.

Along with the *A* and *k* values, the Olsen-P_i values were tested for influences of soil clay content, C_{org}, soil pH, temperature, precipitation and P export, although the influence of these variables were expected to be lower compared to the effect of fertilizer application history (see Section 4.2.1).

4.1.2 | The *A* values

For the majority of the P0 treatments the introduction of an asymptote improved the model fit; of 96 P0 treatments, 52 showed a significant asymptote. This shows, that soils often reach a level of Olsen-P which stays stable over many years.

We were expecting very low asymptotes similar to the results of Johnston et al. (2016), where modelling led to very well-defined curves with low asymptotes in the range of 0.6–6.0 mg Olsen-P kg^{-1}, although by using a combination of several P0 treatments shifted in time (artificial chronosequence).

While several P0 treatments in our study showed well defined curves with asymptotes in Olsen-P areas similar to results of Johnston et al. (2016), an astonishing number of treatments resulted in very high asymptotes (e.g. Figure 4c, Borris: 31.5 mg Olsen-P kg^{-1}; Fuchsenbigl E: 109.4 mg Olsen-P kg^{-1}). Others did not show any decrease over the years of cropping without P fertilizer application even though Olsen-P concentrations were high, implying an asymptote has already been reached at that high level. Meanwhile, many fertilizer recommendations set their target ranges for optimum yield production way below these asymptotes (e.g. 20 mg Olsen P kg^{-1}; Knudsen, 2008, see Figure 5). Of 52 significant *A* values, 25 lay above 20 mg Olsen-P kg^{-1}. It is unlikely, that Olsen-P levels will never decrease further, but there might be various reasons for lack of Olsen-P decrease, inducing these high asymptotes.

In an isolated soil layer, the existence of a definite asymptote of minimum obtainable Olsen-P is not realistic, since this would imply an inexhaustible P supply by the soil. However, P replenishment from less available pools may maintain high levels of STP for many years and in practice, P can be added from various sources. Total P contents were not available for most of our P0 treatments, and therefore, they have not been examined. Nonetheless, the findings of Schulte et al. (2010) show a reduction of the Olsen-P decrease rate connected to high total P values (possibly associated to a high P sorption capacity) that could have the potential to result in a temporary steady state which in a restricted timeframe, appears as an asymptote. In Johnston et al. (2016), varying total P contents and rates of transfer of P between pools of different availability are also considered as a major influence on the shape of the decrease curves. Next to high total P values induced by high previous fertilizer application rates, supply from soil parent material with high P content (Porder & Ramachandran, 2013), for instance, apatite (e.g. in Fuchsenbigl), might also contribute to high asymptotes. Such calcium phosphates are usually not plant available and not extractable by most STP methods (exceptions are AL and DL; Steinfurth et al., 2021), but might become plant available and extractable in the long-term. In addition, high contents of amorphous Al- or Fe-(hydr)oxides (high P sorption capacity) may withhold P from being plant available in the short-term, while being extractable by some STP methods (Pedersen et al., 2023).

Several experiments showed high STP values in their subsoils with some degree of exchange with the topsoil being possible as already assumed for the experiments of Halle (Merbach et al., 2011) and Rostock (Hu et al., 2022). In general, exploitation of P from deeper soil layers or from nearby fertilized plots by roots of the unfertilized plants cannot be ruled out. Since regularly measured STP values of subsoils were only available for a few P0 treatments, we refrained from a further investigation on this topic.

Though rather unlikely for most experiments, there may also be unplanned effects of the setup of field experiments, whose impact may accumulate over the long run-time. For instance, the plot size of the included experiments varied between 15 and 1600 m^2 with buffer zones between plots not always existing. Since most experiments include (partially excessive) P fertilizer application on nearby plots and since most plots are regularly ploughed, in some cases a carry-over from highly P fertilized soil might be possible. This is a problem already recognized by Sibbesen et al. (2000), which is often avoided by sampling in the centre of the plot (Rubæk & Sibbesen, 2000). The exact risk of such P translocation throughout the used P0 treatments is hard to evaluate, since the ploughing regime was often not clearly defined and effects of STP values of surrounding plots were not well comparable because of variation and partially vague definition of plot sizes, buffer zones and ploughing regime. For the P0 treatments of this study, there was no significant correlation between Olsen-P_i, *A* or *k* and plot size (see Figure S7), but this is no proof that there are no individual P0 treatments with this issue.

Additional marginal sources of P input may be atmospheric deposition or erosion from higher areas (Tipping et al., 2014), however, we did not have access to according data or reason to expect large impacts of such sources.

The strong correlation between Olsen-P_i and *A* values showcases that the same dynamics of soil P sorption capacity and P replenishment from less available pools, as well as possible P input from various sources, likely effects both parameters.

4.1.3 | The *k* values

To be able to compare our *k* values with results of other studies, those need to be also based on exponential decay functions dependent on time in years with or without asymptotes. In Johnston et al. (2016), based on the same equation used here, eight British experiments/treatments showed a range of 0.043–0.116 for *k*, which fits in the lower mid-range of our results. Since the decrease curves in Johnston et al. (2016) have been compiled from several different P0 treatments of a given experiment, their results are based on more, partially overlapping data. Therefore, and for reasons of the lower number and variance of locations, it makes sense that resulting coefficients of decrease (*k*) show a narrower range of values. Since two of the experiments examined in Johnston et al. (2016) are also part of our study, but without combining several different treatments into artificial chronosequences, there is an opportunity for the comparison of results. For Saxmundham Rotation II, Johnston et al. (2016) found a k value of 0.072 yr^{-1} with an A value of 2.0 mg Olsen-P kg^{-1}. This aligns well with our findings for Saxmundham H ($k = 0.068$ yr^{-1}, $A = 2.05$ mg Olsen-P kg^{-1}, both not significant), while results of other P0 treatments of Saxmundham showed higher k and A values. For the Rothamsted Exhaustion Land experiment, Johnston et al. (2016) found a k value of 0.105 yr^{-1} with an A value of 1.8 mg kg^{-1} Olsen-P. In our study, two of five treatments of this experiment showed a significant k value (0.098 yr^{-1} and 0.196 yr^{-1}) with asymptotes of 3.94 and 3.85 mg kg^{-1} Olsen-P. Considering the methodical differences, the results of Johnston et al. (2016) and our study are reasonably comparable.

Other comparable k values can be found in Schulte et al. (2010; STP method: Morgan's extraction; eight Irish grassland locations; exponential decay curve without an asymptote). Decrease rates (k) ranged between 0.2 yr^{-1} and 0.6 yr^{-1}, which corresponds to the upper range of our values, considering that there is only one significant k value above 0.6 yr^{-1} in our study. In contrast, Dodd et al. (2012; STP method: Olsen, nine treatments on New Zealand grasslands) also used an exponential decay function without asymptote, resulting in k values between 0.007 yr^{-1} and 0.038 yr^{-1}, falling into the lower range of our results. In these two studies, potential influences of management (grassland versus agricultural fields), the use of Morgan's extraction (in case of Schulte et al. (2010); not used in any of the experiments included in our study) and different soil characteristics might affect comparability.

Olsen-P regressions of various P0 treatments resulted in significant Olsen-P_i values and apparently lower significant A values, but without significant k (see Figure 4c). While usually this would be interpreted as no significant Olsen-P decrease at all (since k is not significantly different from zero), it might also be a sign that the range of Olsen-P decrease (Olsen-P_i minus A) is often rather clear, while the rate of decrease per year is vague. This is making it difficult to pin down a point in time at which critical P values are reached. This is unfortunate considering that the timeframe of decrease in connection with critical P values and potential yield loss (see e.g. Eichler-Löbermann et al., 2021; Nawara et al., 2017; Steinfurth et al., 2022) is of great interest for farmers (Johnston et al., 2016), making k a parameter of high interest in this study. As shown in Figure 5, depending on the k value, the time until a critical value is reached may vary strongly.

Total omission of P fertilizer application can have negative effects on yield even at high STP values (Steinfurth et al., 2022), while fertilizer application rates below P export often show the same yield effect as higher rates (Valkama et al., 2009). Most STP methods used for agricultural purposes are quantity tests, which mainly give information on P becoming available over several months, while directly available P might be reduced under omitted P fertilizer application, leading to high STP values, even though current P availability is low (Pedersen et al., 2023). Fresh P fertilizer application may increase directly available P. Therefore, a reduction of P fertilizer application instead of a complete omission might be a rational alternative for farmers. Such an approach will also lead to STP decrease, but at a slower pace (von Arb et al., 2021). Additional intensity tests (e.g. $CaCl_2$-P), mainly extracting directly available P, can give more insight into actual P availability (Pedersen et al., 2023).

For cases without any obvious Olsen-P decrease or even Olsen-P increase (negative k value), causes might be processes as described in Section 4.1.2 (replenishment of P from less available pools, subsoil or surrounding plots). In addition, changing pH values throughout the runtime of the experiment may impact STP development, because of the influence of pH on the extraction capacity of different STP methods (Steinfurth et al., 2021). The development of pH could not always be checked, since some experiments did not include regular testing of soil pH (see Table S1).

4.2 | Effects of predictor variables on model parameters

4.2.1 | Fixed effects

After stepwise selection, the clay content of the soil was included in the models for Olsen-P_i and A (negative influence in both cases, meaning higher clay contents led to lower Olsen-P_i and A values). The study of Johnston et al. (2016) showed a similar tendency with the location with the lowest clay content exerting the highest asymptote. These results are rather surprising, considering that high clay contents would be expected to result in a higher capacity for P replenishment compared with soils of lower clay content (Morel et al., 2000). However, the higher P sorption capacity of clay-rich soils, mainly because of higher contents of amorphous Al- and Fe-(hydr)oxides (Eriksson et al., 2015), might hamper extraction, thereby resulting in low STP values even though high amounts of P are present (high total P). Nonetheless, the assumption of Johnston et al. (2016) that high C_{org} values lead to higher rates of Olsen-P decrease because P binding sites with lower bonding energy could not be proven in our study.

The pH value did not show a notable impact on any of the parameters, a possible reason being that the extraction strength of the original extraction method is affected differently by soil pH, for example, because of different pH values of the extracting solutions (e.g. CAL being an acid (Schüller, 1969) and Olsen being an alkaline (Olsen et al., 1954) extraction solution). Since these differences are only accounted for in the conversion between the AL and the Olsen method (see Table 2 and Figure S2), a combination of values determined by different methods may not show clear pH-dependent tendencies. However, it should be kept in mind, that pH values can influence plant availability of P independent of STP values. For example, von Tucher et al. (2018) showed, that lower STP values were required for adequate growth when the pH value was increased by liming.

Temperature and precipitation (via soil moisture) have been shown to influence P availability and uptake by plants (Mackay & Barber, 1984, 1985; Ylivainio & Peltovuori, 2012), with increasing values leading to increased P availability, uptake, and therefore, export. However, drought stress under high temperatures would decrease P availability and uptake (He & Dijkstra, 2014). An additional effect of increased precipitation can, depending on the water balance and soil texture, be an increase in P leaching (Riddle et al., 2018). Two of our P0 treatments received irrigation, which will contribute to the precipitation effect, and therefore, was included in the precipitation values. The effect of this inclusion was tested and found to not have a relevant influence on the results. While precipitation and temperature did not show a strong correlation with P export, high precipitation indeed lowered Olsen-P_i and A values. In contrast, high temperature and precipitation values were associated with slower Olsen-P decrease (negative influence on k), which may occur because of increased P replenishment under such conditions (Zhang et al., 2020).

P export is the main negative term in the P balance, and therefore, can be expected to have a strong influence on P decrease. In some studies, the P balance or cumulative P export are used as reference for STP development instead of time (Appelhans et al., 2020; Messiga et al., 2010). However, in our study, P export was not one of the predictor variables included in the models for Olsen-P_i, A or k after stepwise selection. Though there were no strong correlations between P export and any other predictor variables individually, P export can still be expected to be partially dependent on these other variables combined, as well as not considered variables like Total P or subsoil P, which might mask its effects.

The in general low amount of variation explained by the fixed effects is not surprising, considering that various variables suspected to influence the parameters (e.g. content of Al- and Fe-(hydr)oxides, Total P, subsoil P) could not be investigated owing to lack of data. Other variables possibly influencing the other predictor variables or the parameters, were often not recorded in detail or changed throughout the timespan of the experiment, so that a reliable analysis was not possible. An example is the ploughing regime, which, together with bioturbation and tillage erosion can affects the distribution of P in the soil layers (Rubæk et al., 2013). While tillage erosion is unlikely to have had a strong effect in our P0 treatments, since those were usually not positioned at a slope, most of them were ploughed to some degree. Moreover, the ploughing regime as well as incorporation or removal of crop residues affects C_{org} values (Moraru & Rusu, 2010; Spiegel et al., 2018).

4.2.2 | Random effects

The inclusion of the STP method as a predictor variable was initially considered to check for varying patterns of STP development because of different extraction mechanisms and possible errors of conversion (see Figures S1 and S2 and Steinfurth et al., 2021). However, the original STP methods also turned out to form clusters among the P0 treatments in regard to other predictor variables (see Figure 3), fertilizer application history and characteristics of the experimental setups. This is caused by experiments from the same country with a narrower range of soils, climate conditions and fertilizer strategies usually using the same method, as well as some institutions conducting several experiments, thereby eliminating some potential causes of variation (similar experimental setup, same laboratory procedure etc.). For instance, all of the experiments using the $H_2O–CO_2$ method were conducted by the same institution with a very similar experimental setup (Hirte et al., 2021). This leads to the high proportion of variation explained by the original STP method.

5 | CONCLUSIONS

This study revealed large variation in STP development between different P0 treatments with a significant rate of STP decrease (significant positive k value) only found in 35 of 96 P0 treatments. While several cases without significant k values still showed some indication of overall Olsen-P decrease (significant Olsen-P_i and considerably lower significant A values), there were also cases without obvious Olsen-P decrease, implying that A had already been reached, and even cases showing a slight increase in Olsen-P over years without P fertilizer application.

Of the commonly measured variables soil clay content, pH, C_{org}, precipitation, temperature and P export, the most prominent effects were caused by average annual precipitation, temperature or soil clay content. Nonetheless, the variation explained by these variables was rather low, implying that these variables are not sufficient for reliable prediction of STP development under omitted P fertilizer application. This lack of power of prediction as well as the cases without Olsen-P decrease or with unexpectedly high asymptotes imply a large relevance of additional variables, predominantly the P sorption capacity of soils, total P and subsoil P, but also soil management.

In combination with critical STP values for optimum crop yield, provided by other publications, our results give some indications on what to expect if P fertilizer application is omitted. However, for reliable predictions of STP development, the inclusion of further measurements (e.g. maximum P sorption capacity, total P and subsoil P) in future experiments is highly recommended.

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CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

Data of individual experiments can be shared on request and upon agreement of the corresponding data providers.

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SUPPORTING INFORMATION

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