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Effect of increasing rate of P fertilization on available P content in soil and plant uptake: implications for P management

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ABSTRACT

The application of phosphorus (P) is necessary for sustainable crop production. Its application rate is often based on soil analysis. However, the P availability is not always properly evaluated for optimal P management. The effect of long-term P fertilization on soil P availability, yield, and plant uptake of P was investigated using data from a long-term field experiment. We hypothesized that: 1) an increasing rate of P fertilization increases soil P content, yield, and P uptake, and 2) annual change of P uptake and P content increases from negative to positive values at an increasing rate of P addition. Different strategies of P management were evaluated using experimental results. Increasing inputs of P in mineral or organic form increases soil P content. However, the effect on yield is limited and unused P accumulates in soil. High yield ensuring strategy of P fertilization is therefore not useful as a way of P management. Results suggest that keeping soil P content in the range of 50–80 mg P kg⁻¹ and organic fertilization (and probably also legume cropping) are useful ways of using P from fertilizers or soil reserves. Results also suggest that Mehlich III soil test brings useful information for P management.

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KEYWORDS

Mehlich III; phosphorus fertilization; plant phosphorus uptake; soil phosphorus availability

Introduction

Phosphorus (P) is a basic plant nutrient, often limiting plant growth and the yield of agricultural crops (Alewell et al. 2020). Its application to soil in organic or mineral fertilizers is a common practice in intensive agriculture. The rate of P fertilization necessary for appropriate yield is usually estimated on the basis of crop P demand and soil P availability (Klír, Kunzová, and Čermák 2008; Tóth et al. 2014). However, it is very difficult to assess plant availability of soil P because it forms slightly soluble minerals that first need to be dissolved into a plant-available form in the rhizosphere (Hallama et al. 2019). An extraction agent should therefore dissolve P forms that are potentially available for plant uptake during the growing season. Numerous methods have been developed that determine the fraction of P related to plant uptake. One of the most widespread methods is the measurement of P in a soil extract according to Mehlich III (Mehlich 1984; Sedlář et al. 2018). The Mehlich III method demonstrated a relationship between plant yield and soil P content, and limits for low, optimal, or excessive content in soil were estimated accordingly (Hopkins et al. 2018; Hopkins and Hansen 2019; Von Tucher, Hörndl, and Schmidhalter 2018). With a low P content in the soil, crop yield is limited by P. Increasing P availability increases

yield up to the level where plant growth is P-saturated. P availability and P fertilization above this saturation level have no effect on yield. In addition, excessive P application could negatively impact the uptake of other nutrients and microelements, such as Zn (Sedlár et al. 2018; Bindrabán, Dimkpa, and Pandey 2020). A successful analytical assessment of the P-limitation and P-saturation level is therefore very important information for nutrient management, which helps to determine appropriate P input rates (Klír, Kunzová, and Čermák 2008).

On the basis of known features of P in soil, several approaches to P fertilization have been developed. Currently, the usual method of P management in agriculture is P fertilization of the soil, not of the plants. P is either applied according to its available content in the soil or is added at a rate that maintains a balance between inputs and outputs. Country-specific tables of suggested P-application rates have been developed (Klír, Kunzová, and Čermák 2008). Some approaches suggest P application at a higher rate than demanded by the plant because of the low availability of P in fertilizers (Menezes-Blackburn et al. 2018). In contrast to the usual fertilization of soil, which involves applying large amounts of insoluble P, Withers et al. (2014) suggest fertilization of plants as an alternative method that adds a relatively small amount of P in a highly available form. Considering the low solubility of soil P, its solubilization through biological processes in the soil is a very important factor in soil P availability. Biological activity is supported by sufficient inputs of organic matter from organic fertilizers (e.g. manure, compost, and cattle slurry). In addition, the roots of some crops have the ability to solubilize and uptake P. The strong capacity for P solubilization is usually attributed to legumes – their large root systems produce exudates that directly interact with P minerals and indirectly support the activity of microbes, which release their own solubilizing agents (e.g. CO₂ and organic acids). The application of P using organic fertilizers or together with organic fertilizers is therefore suggested in most manuals of P fertilization (Klír, Kunzová, and Čermák 2008; Menezes-Blackburn et al. 2018; Hallama et al. 2019).

The effect of long-term P fertilization on soil P availability, yield, and plant uptake of P was investigated using data from a long-term field experiment. The effect of an increasing P fertilization rate on yield, plant P uptake, and P content in soil was estimated. The following hypotheses were tested: 1) up to some level, an increasing rate of P fertilization increases soil available P content, yield, and P uptake and 2) annual change of P uptake and P content increases from negative to positive values at an increasing rate of P addition. The obtained data were used to evaluate different strategies for P fertilization. The use of the Mehlich III method for estimating P availability is discussed.

Materials and methods

Crop sequence and treatments in a long-term field experiment

A long-term field experiment was established at 6 stations of the Institute for Supervising and Testing in Agriculture. Basic characteristics of the field stations and the year of experiment establishment at each station are given in Table 1; crop sequence used in the experiment is given in Table 2. Crop sequence was multiple times repeated during the time course of the experiment, after the last crop in the crop sequence (barley), the subsequent crop sequence started with alfalfa (clover) as the first crop. According to the Czech classification, stations are divided into sugarbeet, and potato production areas. Stations HOR, CHT, JAR, and HRA belong to potato area, where potato is used in crop sequence as row crop. Stations PJA and UHO belong to sugarbeet area where sugarbeet represents row crops.

Rates of fertilization of each crop in the crop sequence are given in Table 3. P was applied as superphosphate, and K as potassium chloride, both fertilizers being applied in the fall preceding

Table 1. Characteristics of field stations.

Station	Abbreviation	Area	Year of experiment establishment	Elevation (m)	Mean precipitation (mm)	Mean temperature (°C)	Soil type
Horažďovice	HOR	PA	1978	472	585	7.8	C
Chrastava	CHT	PA	1977	345	738	8.0	L
Jaroměřice	JAR	PA	1975	425	481	8.0	L
Pusté Jakartice	PJA	SA	1979	290	548	8.3	L
Hradec nad Svitavou.	HRA	PA	1981	460	599	7.5	L
Uherský Ostroh	UHO	SA	1972	196	521	9.2	C

PA: potato production area; SA: sugarbeet production area

Soil types abbreviated as C, L, and Ch correspond to soil types Cambisol, Luvisol, and Chernozem, respectively.

Table 2. Crop sequence of the field experiment.

Year of crop sequence	Sugarbeet area	Potato area
1	Alfalfa	Red clover
2	Alfalfa	Red clover
3	Winter wheat	Winter wheat
4	Potato	Potato
5	Winter wheat	Winter wheat
6	Spring barley	Spring barley
7	Sugarbeet	Potato
8	Spring barley	Spring barley

Table 3. Rates of fertilization.

Treatment	Rate of mineral fertilization (kg ha ⁻¹)			Rate of manure application (t ha ⁻¹)	Rate of P input in manure (kg P ha ⁻¹)	Liming
	N	P	K			
Control	0	0	0	0	0	0
Manure	0	0	0	40	14	According to pH value
P0	90	0	66		14	
P1	90	13	66		14	
P2	90	26	66		14	
P3	90	52	66		14	

crop establishment. Nitrogen was applied as ammonium sulfate before seeding and calcium ammonium nitrate was applied as a side dressing during vegetation.

Manure was applied to all fertilized treatments twice in all crop sequences: before sugarbeet or potato growing. Liming was performed in all treatments except for the control. The rate of lime addition was estimated according to pH value. At the lowest pH values in the range 4.6–5 annual rate was 0.7 t Ca ha⁻¹. It was applied at four-year intervals in one dose of CaO. No liming was performed above pH 6.5.

Each treatment had 6 replications organized as subplots using block design. The area of the individual subplot was 20 m².

Parameters estimated in the field experiment

The yield of the harvested products was determined for each subplot of each treatment and each crop. Harvested products were grain of winter wheat and barley, sugar beet in sugar beet area (stations PJA and UHO), and potatoe in potato area (stations HOR, CHT, JAR, and HRA). Samples of harvested products were mixed from six subsamples, each subsample being collected from one subplot of each treatment. In total, 1 kg of each product was collected. Harvested products were air-dried and ground before analysis. The P content of the harvested products was

determined using the method described by Zbíral et al. (2014) and Sedlár et al. (2018). Soil samples were collected each year after harvest from soil depth 0–30 cm at each subplot of each treatment. One kilogram of samples was air-dried and sieved using 2 mm sieve. P availability in soil was determined using extraction according to the Mehlich III method (Mehlich 1984; Zbíral et al. 2016; Sedlár et al. 2018).

Statistics

Data concerning the yield of winter wheat, barley, sugarbeet and potato, plant P uptake, and P availability in soil were evaluated. For each location and treatment, data collected during the whole period of the experiment were used for analysis. The effect of treatment was tested using two-way ANOVA, with the independent factors being treatment and year (Zar 2010). The differences between treatments were determined using the Tukey's test. Analyses were performed separately for all treatments (control, manure, P0–P3) and for treatments which differed only by P fertilization rate (P0–P3).

Long-term changes were evaluated as a regression of the measured parameters and time. Annual changes in the parameters were calculated. Long-term changes in soil P content were not linear. Therefore, results were divided into three distinct periods with linear changes and analyzed separately. Statistica version 13 software (Tibco, Palo Alto, CA, USA) was used for statistical processing of the data.

Results

Effect of fertilization on crop yield

At most of the stations, winter wheat yield was insignificantly increased after manure application and a significant increase was observed following application of NPK at the rate P0 (Figure 1(A)). A higher rate of fertilization had no additional effect on yield. At the station UHO, no significant effect of fertilization on winter wheat yield was observed (Figure 1(A)).

When wheat yields were evaluated separately for treatments P0–P3, increasing the rate of P significantly increased the yield only at the stations Jar and UHO (Figure 2(A)). However, the differences were small, and they were not higher than 3%.

The same level of spring barley yield was attained in the control treatment and in the one treated with manure (Figure 1(B)). Treatments fertilized with P at the rates P0–P3 had significantly higher yield than the control treatment, with the differences between P0 and P3 being insignificant.

Comparison of treatments P0–P3 showed a significant increase of barley yield at 4 of 6 stations, the difference being up to 9%. Insignificant differences were observed at the stations HRA and UHO (Figure 2(B)).

The yield of sugarbeet was increased by manure application, but this effect was significant only at the station PJA. Increasing the P fertilization rate above P0 had no effect on yield (Figure 1(C)).

Differences between separately evaluated treatments P0–P3 were significant at the station PJA.

The yield of potato fertilized with manure was insignificantly higher than the yield of the control treatment at all stations (Figure 1(D)). The yield of treatment P0 was significantly higher than the yield of the control, but it did not significantly differ from the yield of treatments P1–P3. Comparison of treatments P0–P3 documented a significant increase in yields with an increasing rate of P addition at stations HOR, CHR, and JAR (Figure 2(C)).

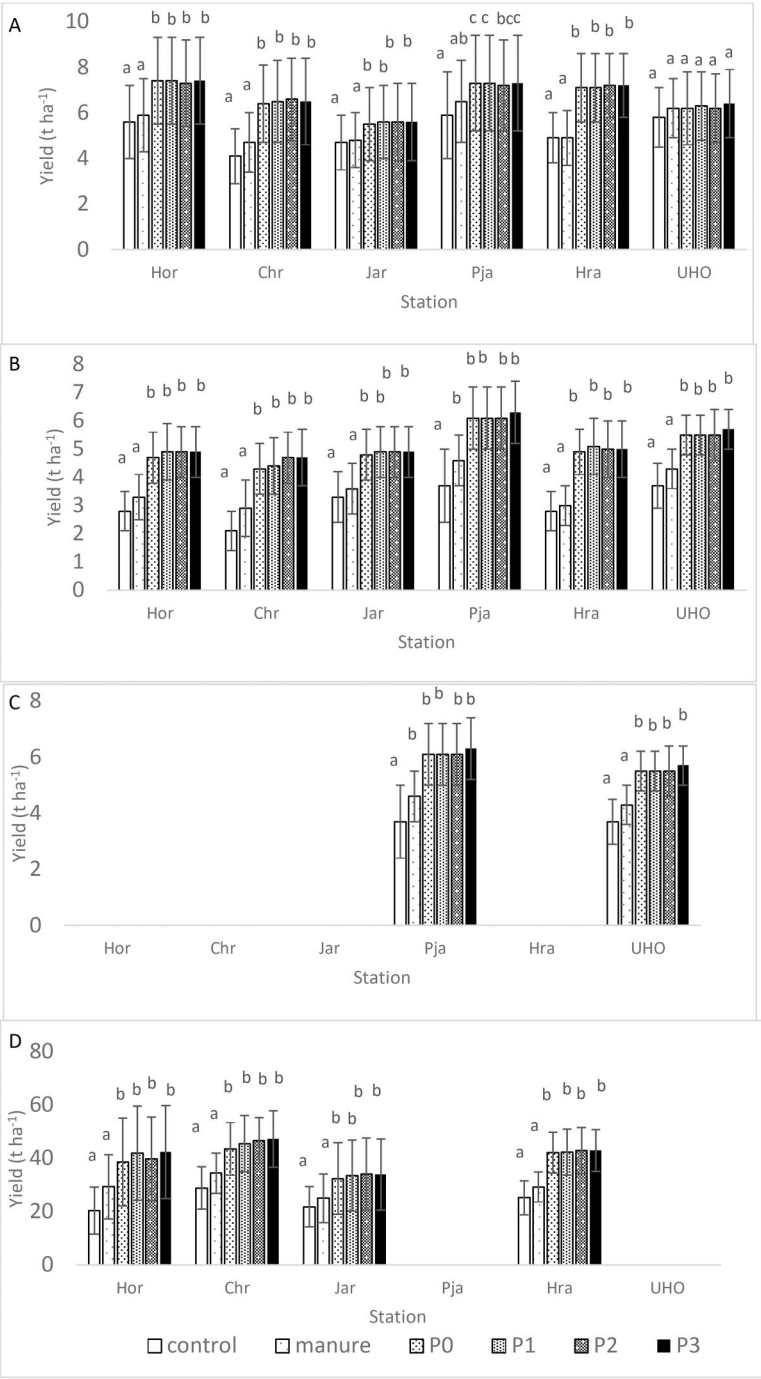


Figure 1. Yield (t ha⁻¹) of winter wheat (A), spring barley (B), sugarbeet (C), and potato (D) during a long-term field experiment for 6 stations with different levels of P fertilization. The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively. The treatments P0–P3 correspond to the application of manure, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha⁻¹ (P0), 13 kg P ha⁻¹ (P1), 26 kg P ha⁻¹ (P2), and 52 kg P ha⁻¹ (P3). Data represent means and standard deviations. Different letters indicate significant differences between treatments (ANOVA and Tukey's test, $p < 0.05$).

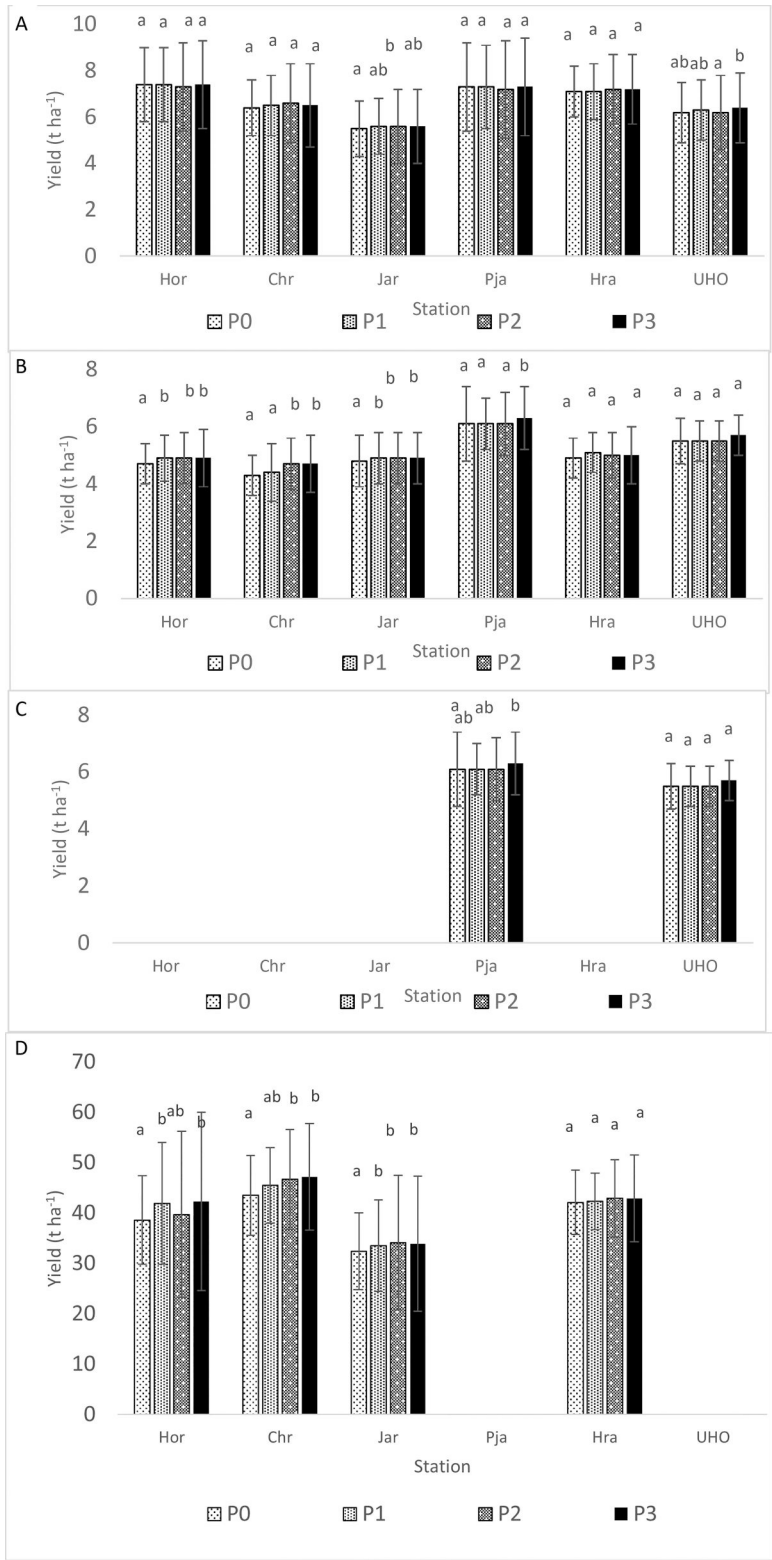


Figure 2. Yield (t ha⁻¹) of winter wheat (A), spring barley (B), sugarbeet (C), and potato (D) during a long-term field experiment for 6 stations with different levels of P fertilization. The treatments P0–P3 correspond to the application of manure, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha⁻¹ (P0), 13 kg P ha⁻¹ (P1), 26 kg P ha⁻¹ (P2) and 52 kg P ha⁻¹ (P3). Data represent means and standard deviations. Different letters indicate significant differences between treatments (ANOVA and Tukey's test, $p < 0.05$).

Crop P uptake

At most stations, manure application insignificantly increased P uptake, and fertilization at the rate P0 significantly increased P uptake, compared with the control (Figure 3(A)). Fertilization at the rate P0 also increased P uptake in comparison with the manure treatment. The highest rate, P3, significantly increased P uptake above the level of uptake at P0 at five stations.

Significant differences were also observed between treatments P0–P3 (Figure 3(B)). The effect of increasing the P rate was only insignificant at the station PJA. When linear regression was calculated, P uptake was correlated with the rate of P addition, the slope of regression being 0.064.

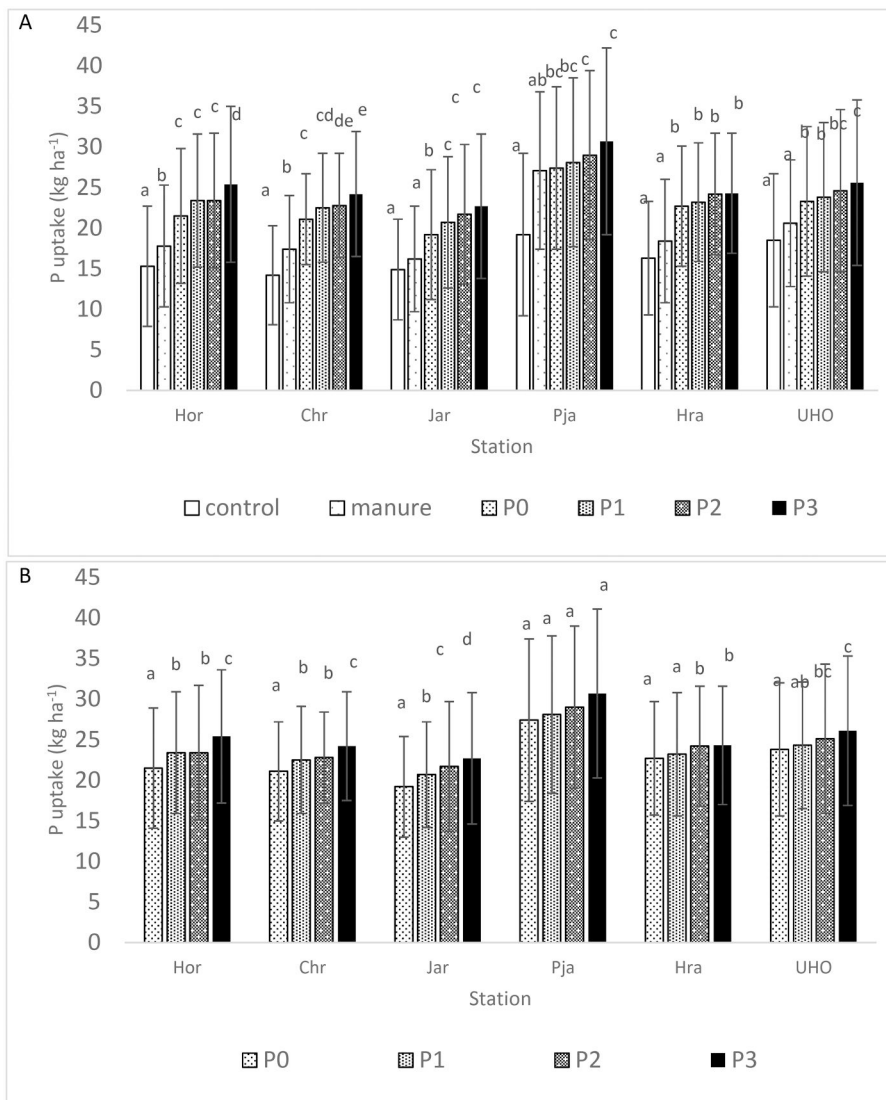


Figure 3. Mean annual P uptake (kg ha⁻¹) in all treatments (A) and in four selected treatments with increasing rate of P only (B) in the field experiment. The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively. The treatments P0–P3 correspond to the application of manure twice in the crop sequence, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha⁻¹ (P0), 13 kg P ha⁻¹ (P1), 26 kg P ha⁻¹ (P2), and 52 kg P ha⁻¹ (P3). Data represent means and standard deviations. Different letters indicate significant differences between treatments (ANOVA and Tukey's test, $p < 0.05$).

The expected decline in P uptake with a negative P balance was only observed for the control treatment at the station UHO (Figure 4 and Table 4).

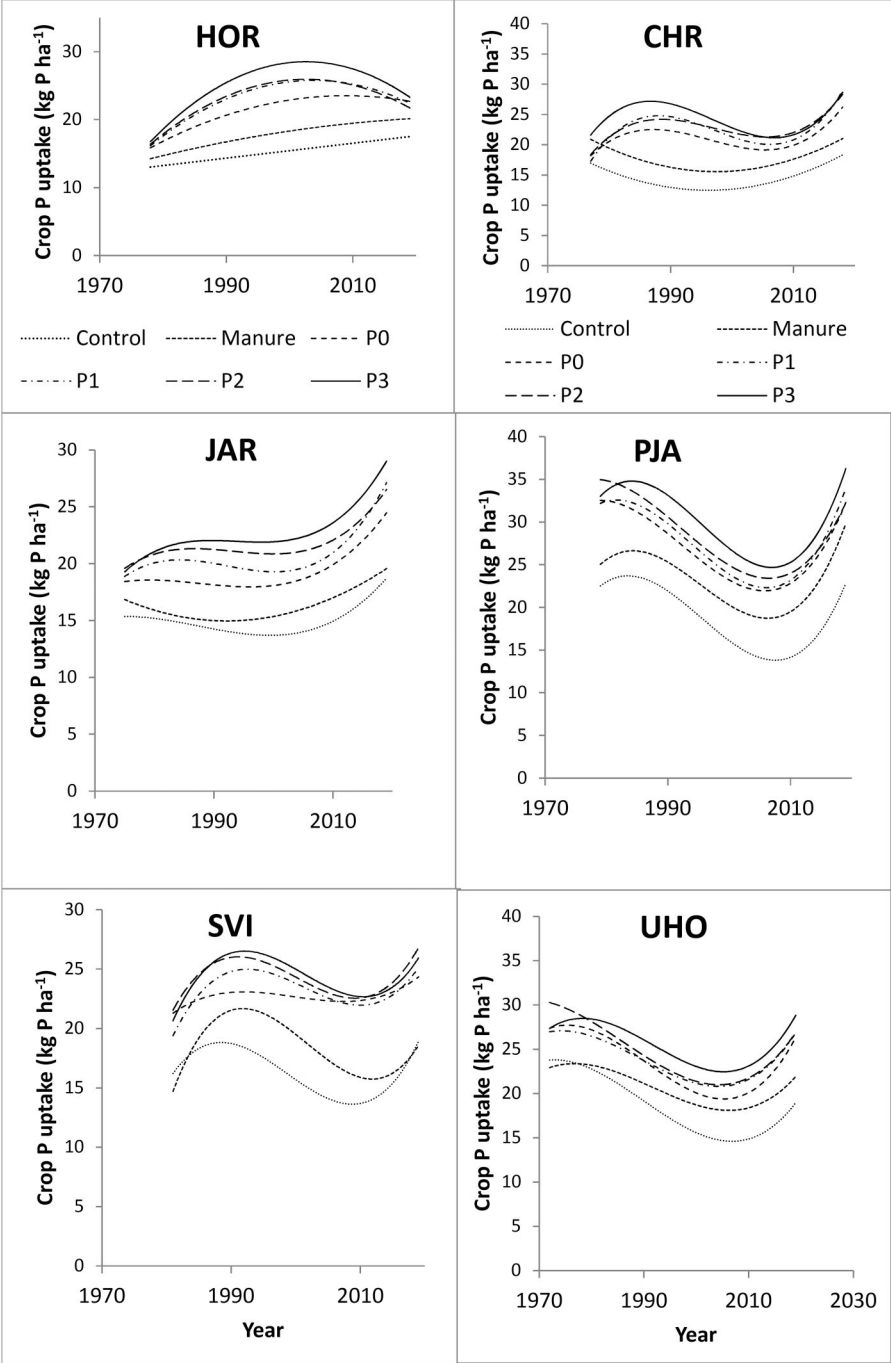


Figure 4. Annual rates of crop P uptake (kg ha⁻¹) of differently fertilized treatments in the field experiment. The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively. The treatments P0–P3 correspond to the application of manure twice in the crop sequence, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha⁻¹ (P0), 13 kg P ha⁻¹ (P1), 26 kg P ha⁻¹ (P2), and 52 kg P ha⁻¹ (P3).

Table 4. Mean annual change in the P uptake of all crops during the time course of the field experiment ($\text{kg P ha}^{-1}\text{year}^{-1}$). The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively.

Station	Treatment					
	Control	Manure	P0	P1	P2	P3
HOR, $n = 42$	0.11	0.14	0.17	0.15	0.13	0.16
CHR, $n = 43$	0.03	0.005	0.02	0.02	0.05	−0.06
JAR, $n = 45$	0.03	0.06	0.09	0.09	0.09	0.13
PJA, $n = 41$	−0.20	−0.10	−0.17	−0.16	−0.22	−0.17
HRA, $n = 39$	−0.05	−0.04	0.08	0.06	0.04	0.04
UHO, $n = 48$	−0.20	−0.11	−0.15	−0.1	−0.15	−0.10

The treatments P0–P3 correspond to the application of manure twice in the crop sequence, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha^{-1} (P0), 13 kg P ha^{-1} (P1), 26 kg P ha^{-1} (P2), and 52 kg P ha^{-1} (P3). Data represent the slope of the regression of annual P uptake and time. Significant values are indicated in bold.

Soil P content

Increasing the rate of P fertilization significantly increased the available P content in the soil (Figures 5 and 6). When treatments with increasing rates of P (treatments P0–P3) were evaluated separately, all differences were significant.

Values fluctuated during the experiment (Figure 5) with periods of soil P accumulation and depletion. The supposed trend of P depletion at low values of P addition was however not observed (Table 5).

Soil pH value

The lowest pH value was observed at control treatment at all stations. It was significantly increased by manure application. In all treatments with mineral fertilization, insignificantly lower values were observed in comparison with manure-only treatment (Table 6).

Discussion

Effect of P fertilization on plants and soil

In general, yields of cultivated crops differed widely between differently fertilized treatments. However, it was especially the addition of mineral N that stimulated plant growth and yields. Nitrogen is often considered to be the main yield-limiting nutrient and this crucial effect of N addition has previously been reported for example by Hejcman, Kunzová, and Šrek (2012) or Káš et al. (2016). The lowest effect on yield showed manure-only treatment, despite significant input of nutrients applied in organic fertilizer. However, manure is applied twice in crop sequence and it is relatively poor as a source of easily available N. It has a long-term effect on fertility, but the immediate manure addition effect on crop yields usually realized only with added soluble N (Hijbeek et al. 2018). Therefore, the most significant effect on the yield of crops at most of the stations had an addition of N and K together with manure application (treatment P0) (Figure 1). Addition of increasing P rates with this level of N and K fertilization had relatively weak effect. It is probably the result of long-term P accumulation in soil that created a strong legacy effect overriding the effect of added P (Barrow, Roy, and Debnath 2022). The effect of mineral P fertilizer addition in treatments P1–P3 was only significant when the effect of increasing the rate of P was evaluated separately. The highest gain in yield was observed for barley and potato, where an increase in yield was up to 9%. It is in agreement with the known demands of both crops on nutrients in easily available forms (Buczko et al. 2018; Hopkins and Hansen 2019).

Crop P uptake also increased up to the highest rate of fertilization. However, the increase in the P application rate was 52 kg P ha^{-1} , while P uptake increased by only 3–4 kg P ha^{-1} . The

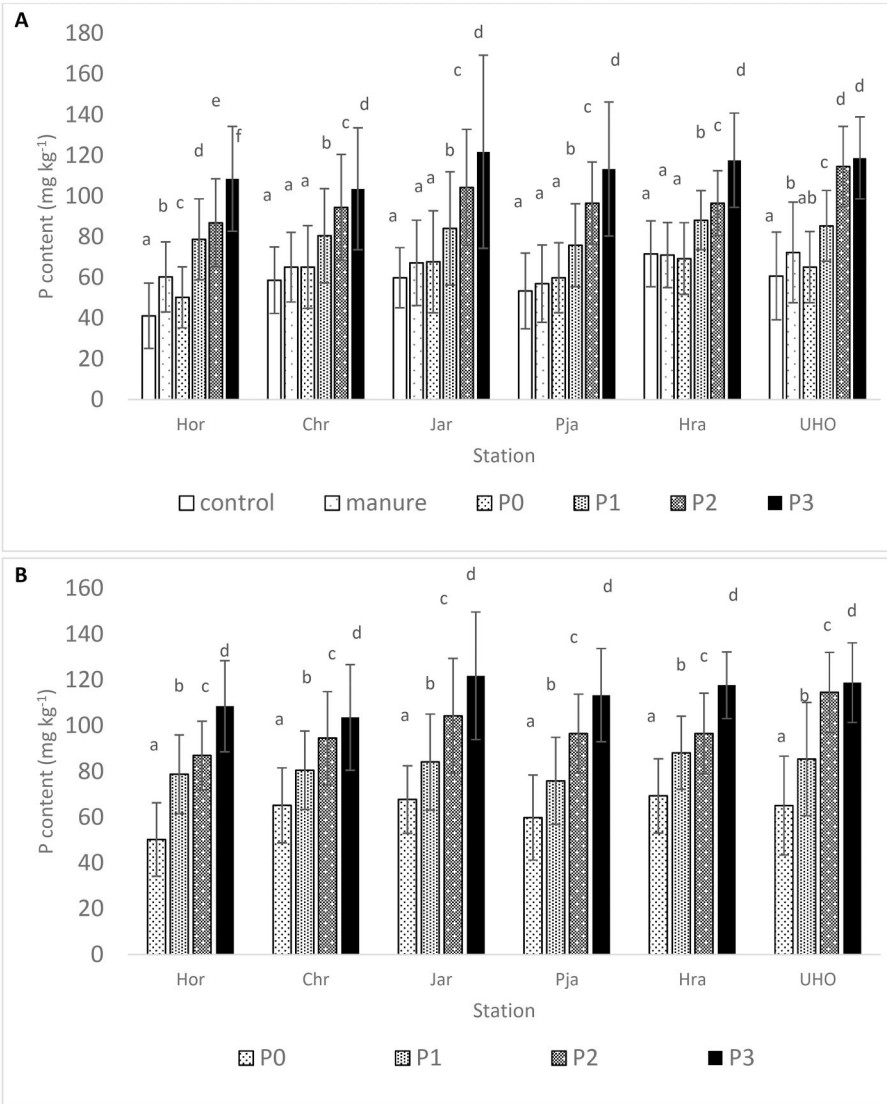


Figure 5. Mean available P content in the soil of differently fertilized treatments (A) and selected treatments with increasing rate of P fertilization (B) in the field experiment (mg P kg⁻¹). The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively. The treatments P0–P3 correspond to the application of manure twice in the crop sequence, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha⁻¹ (P0), 13 kg P ha⁻¹ (P1), 26 kg P ha⁻¹ (P2), and 52 kg P ha⁻¹ (P3). Data represent means and standard deviations. Different letters indicate significant differences between treatments (ANOVA and Tukey's test, $p < 0.05$).

slope of linear regression was about 0.06, which means that only 60 g of P from each kilogram of P fertilizer, which is 6%, was taken up by plants. A higher rate of P fertilization than P0 is therefore very inefficient as source of P and most of P added in mineral fertilizer above this rate is left over in the soil and is not fully used by plants (Figure 5). Similar results were also reported by Káš et al. (2016). In their study, the addition of P fertilizer had a limited effect on yield but increased soil available P content. From this point of view, a fertilization rate above P0 has a poor effect, and rates higher than P1 make no sense.

A comparison of crop yields and soil available P content suggests that P content in the range of 50–70 mg P kg⁻¹, achieved at the rate P0, could be classified as optimal P availability.

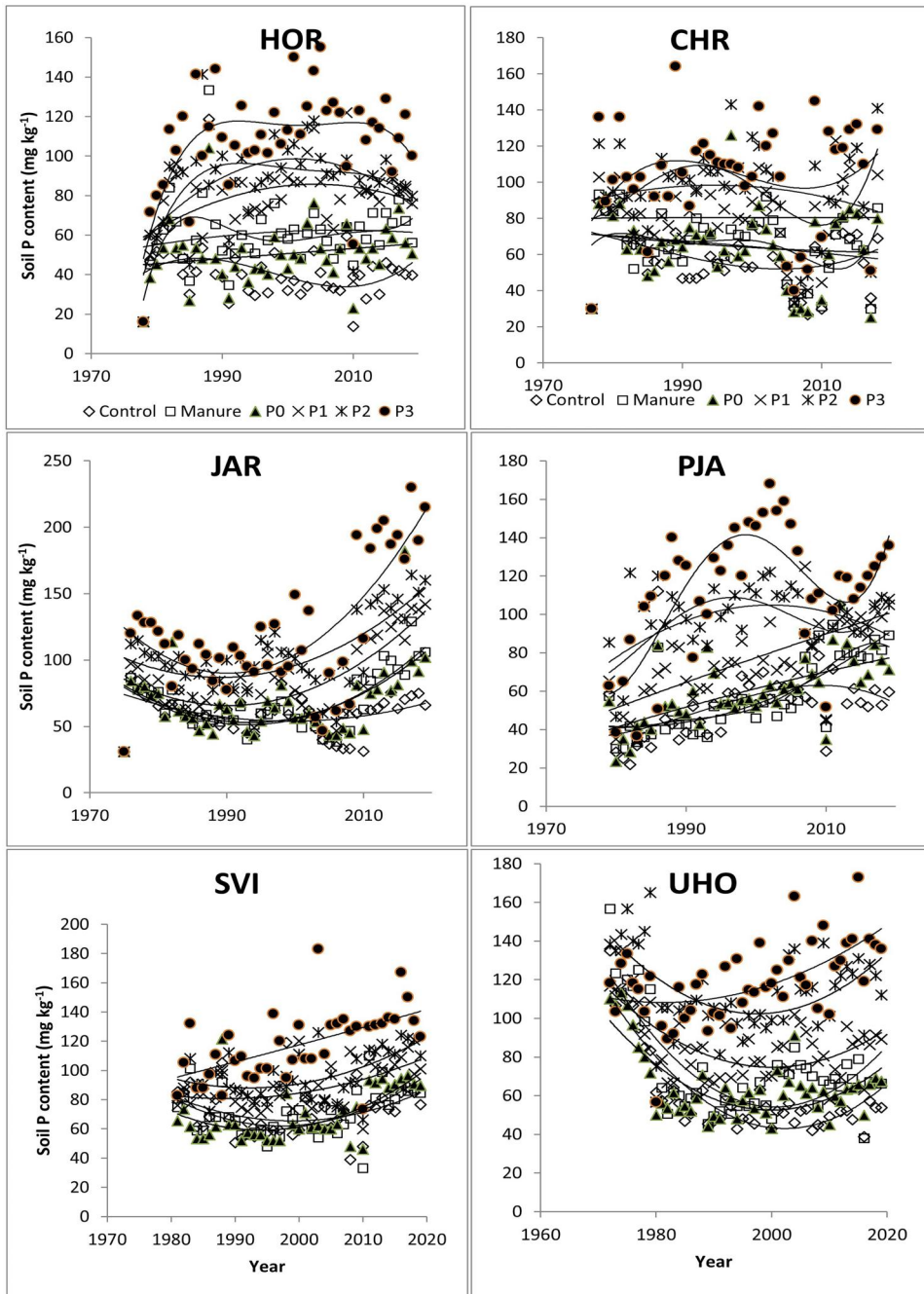


Figure 6. Available P content in the soil of differently fertilized treatments in the field experiment (mg P kg⁻¹). The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively. The treatments P0–P3 correspond to the application of manure twice in the crop sequence, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha⁻¹ (P0), 13 kg P ha⁻¹ (P1), 26 kg P ha⁻¹ (P2), and 52 kg P ha⁻¹ (P3).

However, it is not possible to fully separate the effect of P added in manure and NPK fertilizer from the effect of other nutrients and other indirect effects of applied fertilizers. It is therefore possible that the real limit of sufficient P availability is lower, and applied fertilizers increase yield through the addition of N. Besides this, fertilizers not only affect directly the P availability

Table 5. Mean annual change in soil P content in three distinct periods of a long-term field experiment ($\text{mg P kg}^{-1} \text{ year}^{-1}$).

Station	Period	Treatment					
		Control	Manure	P0	P1	P2	P3
Hor, $n = 42$	72–88	−0.206	0.187	0.261	0.241	0.281	0.580
	89–04	0.141	0.810	1.580	1.760	2.040	1.260
	05–19	0.514	1.030	0.630	0.156	−0.612	−1.258
Chr, $n = 43$	72–88	−1.331	−0.463	−1.494	0.050	1.830	0.539
	89–04	0.870	1.160	0.163	0.040	0.201	−0.398
	05–19	2.150	2.380	2.680	3.840	4.710	4.780
Jar, $n = 45$	72–88	−0.859	−1.138	−1.545	−1.197	−0.176	−0.223
	89–04	0.273	−0.294	−0.251	−1.143	−0.421	−0.622
	05–19	3.199	5.236	5.622	6.704	6.237	10.369
Pja, $n = 41$	72–88	2.677	1.523	2.857	3.767	5.247	8.074
	89–04	1.837	0.956	0.210	0.876	1.536	3.919
	05–19	−0.142	1.866	0.909	1.544	0.497	0.952
HRA, $n = 39$	72–88	0.492	−0.540	3.760	1.410	0.842	−0.921
	89–04	1.360	0.331	0.486	0.698	0.482	1.670
	05–19	1.654	1.880	2.888	1.508	2.710	1.190
UHO, $n = 48$	72–88	−4.873	−5.660	−3.914	−3.157	−3.039	−0.762
	89–04	0.159	1.850	1.559	0.960	1.636	2.456
	05–19	0.432	−0.535	0.391	−0.111	0.351	1.630

The treatments control and manure correspond to an unfertilized control and the application of manure twice in the crop sequence, respectively. The treatments P0–P3 correspond to the application of manure twice in the crop sequence, together with NPK fertilization, with P added at a mean annual rate of 0 kg P ha^{-1} (P0), 13 kg P ha^{-1} (P1), 26 kg P ha^{-1} (P2), and 52 kg P ha^{-1} (P3). Data represent the slope of the regression of annual P uptake and time. Significant values are indicated in bold.

Table 6. Mean pH value during long-term field experiment.

Station	Treatment					
	Control	Manure	P0	P1	P2	P3
HOR, $n = 44$	$5.6 \pm 0.3a$	$6.1 \pm 0.2c$	$5.9 \pm 0.3b$	$5.9 \pm 0.3b$	$5.9 \pm 0.3b$	$5.9 \pm 0.3b$
CHR, $n = 45$	$4.8 \pm 0.4a$	$5.8 \pm 0.4b$	$5.7 \pm 0.5b$	$5.6 \pm 0.4b$	$5.6 \pm 0.5b$	$5.7 \pm 0.4b$
JAR, $n = 47$	$5.3 \pm 0.3a$	$6.2 \pm 0.2c$	$6.0 \pm 0.3b$	$6.0 \pm 0.3b$	$6.1 \pm 0.4b$	$6.0 \pm 0.3b$
PJA, $n = 43$	$5.8 \pm 0.4a$	$6.3 \pm 0.3b$	$6.2 \pm 0.4b$	$6.2 \pm 0.4b$	$6.3 \pm 0.4b$	$6.1 \pm 0.4b$
HRA, $n = 41$	$6.0 \pm 0.4a$	$6.5 \pm 0.3b$	$6.4 \pm 0.4b$	$6.3 \pm 0.4b$	$6.3 \pm 0.4b$	$6.3 \pm 0.4b$
UHO, $n = 50$	$6.8 \pm 0.2 \text{ cd}$	$7.0 \pm 0.2d$	$6.5 \pm 0.3b$	$6.4 \pm 0.3ab$	$6.7 \pm 0.3c$	$6.3 \pm 0.3a$

Different letters indicate significant differences between treatments (ANOVA and Tukey's test, $p < 0.05$).

through its input into soil, but they also change other soil features that change P availability, including microbial activity, organic matter content, and pH value (Káš et al. 2016; Hallama et al. 2019; Kulhánek et al. 2019). In this study, only results concerning pH values are available, biological activity and humus content were not evaluated. The pH value was significantly changed by different rates of N, K, and manure addition. In general, the highest pH values were observed at manure treatment and the lowest ones at control, which is very different trend than this observed for soil P content. Manure fertilization increases pH through the input of cations (Ca, K, and Mg) and the buffering effect of added organic matter. A slightly negative effect of mineral fertilization on pH value could be explained by the acidifying effect of ammonium sulfate used as a source of nitrogen in the experiment. All these changes could affect also soil P availability. However, the effect of pH increase or decrease on soil P availability could not be fully distinguished from other effects of fertilizers and a clear relationship between pH and other measured parameters was not observed. Results were compared with other studies concerning the effect of P availability and P fertilization on yield. Káš et al. (2016) reported a small effect of P fertilization on winter wheat grain yield in soil with P content higher than 100 mg kg^{-1} in a long-term field experiment. Mühlbachová et al. (2016) found a significant increase in barley biomass yield at an increasing rate of P application in soil with a P content of 57 mg kg^{-1} . The reported results suggest that P fertilization has a positive effect on yield for soil P content up to $50\text{--}60 \text{ mg kg}^{-1}$. For

P content higher than 100 mg kg^{-1} , fertilization has no effect. This is in agreement with our results. Comparable data are scarce, but they usually indicate a lower limit for maximal yield, for example Hopkins and Hansen (2019) reports 45 mg P kg^{-1} .

When the effect of P availability on crop yield is being evaluated, the demands of soil organisms should also be considered. Čapek et al. (2018) report the effect of N and P availability on interactions between plants and soil microbes. Although these interactions are seldom studied in fertilization experiments, their impact on P management should not be overlooked.

The expected decline of the P content in soils with a lower rate of P input was not supported by the obtained data. It could be attributed to mobilization from soil reserves. P could be mobilized by the activity of roots or microbial activity. Increasing the inputs of N, K, and other nutrients increases plant P demands, but it can also speed up the process of P mobilization from organic matter and from other insoluble forms. These mechanisms may help to maintain soil P availability despite limited P inputs. A significant, but largely unknown amount of P could also be provided by subsoils (Kautz et al. 2013). Under the conditions of European agriculture, strong evidence exists that long-term P inputs exceeded P outputs. Therefore, large reserves of P are accumulated in soils (Sattari et al. 2012). The storage of a significant amount of P in soil could explain the observed differences between experimental treatments in the studied soils. The significance of accumulated reserves as a source of P has been suggested by, for example, Withers et al. (2014) and Spohn et al. (2016).

Different methods of P fertilization as they relate to experimental results

High yield, ensuring fertilization – high rates ensure maximal attainable yield. It is often argued that P fertilizers should be applied in excess, which ensures sufficient P uptake by plants at the usually low availability of P from fertilizers (Menezes-Blackburn et al. 2018; Blackwell, Darch, and Haslam 2019). This method does not seem to be efficient in terms of the presented results – yield gain at the highest rate of P application (Figure 1) is small (0–5%); it is highly P demanding, and unused P accumulates in soil (Figures 1, 2, and 5).

Use of soil P reserves – the studied soils contain large stores of P, which provides an annual P supply of at least 15 kg P ha^{-1} (Figure 3). This rate of P supply seems to be stable during the time course of the experiment (Table 4). Management of the studied sites was not documented before establishment of the experiment. However, high fertilization rates were commonly used in the preceding period (1950–1970) and the presence of legacy P (Sattari et al. 2012; Menezes-Blackburn et al. 2018) in the soil is probable. The question remains whether P should be further added as fertilizer, or accumulated soil reserves should be preferentially utilized (Withers et al. 2014). The utilization of soil P should be promoted by soil microbial activity, the growing of crops that efficiently uptake P from insoluble forms, and the sufficient application of other nutrients (N, K, S, microelements, etc.) (Menezes-Blackburn et al. 2018; Hallama et al. 2019; Ludewig, Yuan, and Neumann 2019; Schneider et al. 2019; Cui et al. 2021). Under the conditions of the field experiment, the planting of clover or alfalfa should be an important factor for P mobilization from insoluble forms and deeper soil layers (Wollmann et al. 2018; Hallama et al. 2019).

Maintaining P content in soil at the optimal level according to soil analysis – the results suggest that optimal P availability is within the range of $50\text{--}80 \text{ mg kg}^{-1}$. This is higher than the critical values of $25\text{--}35 \text{ mg P kg}^{-1}$ proposed by Malarino (2003). Hopkins et al. (2018) report 55 mg P kg^{-1} as the upper range for responsiveness to P fertilization. However, it is not possible to fully separate the effect of P addition on yield from the effect of the other nutrients applied. Therefore, it is possible that the addition of other essential nutrients (especially N) should lead to a similar effect, even with a lower P content in the soil. The results of this study suggest that at least the accumulation of unused P may be monitored by method Mehlich III.

Maintaining a balance of inputs and outputs – in our study we hypothesized that soil P availability, yield and P uptake decrease with a negative P balance. However, they remained relatively constant, even with the long-term absence of P input for the control treatment (Table 5). This suggests that maintaining a balance was not necessary for sufficient P availability. It is more likely that with a sufficient supply of legacy P from soil reserves, maintaining a balance leads to over-fertilization. However, the effect of a P balance should be more pronounced with a longer time scale. Maintaining a balance of inputs and outputs is therefore controversial without regular soil testing.

Organic fertilization – organic matter of high quality is usually a rich source of plant-available nutrients, including P. In the present experiment, the input of manure significantly contributed to P uptake. The significance of organic fertilization as a P source is also reported by Kulhánek et al. (2019). Organic fertilization is not only a source of P, but it also increases its availability (Dao 2014). Manure, as a source of P, may explain the limited additional effect of P fertilization above the P0 level.

Fertilization of the plant, not the soil – the usual approach to P fertilization is to fertilize the soil, not the plant. However, P is largely immobilized in the soil, and the use of applied P is limited. Methods are therefore sought to apply P directly to a plant with an efficiency as high as possible, such as local fertilization (Jing et al. 2010), foliar application (Mosali et al. 2006), fertilizers based on polyphosphates, etc. (Withers et al. 2014). The presented results suggest that the usual method of P addition increases soil P content, but the real contribution to P uptake is a few kg P ha⁻¹ at the highest rate of P fertilization. The application of P in a highly available form should replace the effect of this highly inefficient input at a relatively low fertilization rate.

Conclusions

Increasing inputs of P in mineral or organic form has a significant, but limited effect on crop yield and plant P uptake. Unused P accumulates in the soil at higher rates of P addition rather than increasing soil fertility. High yield ensuring strategy of P fertilization is therefore not useful as a way of P management. The expected decline of soil P and plant P uptake at a low level of P fertilization was not observed. Large reserves of P in the studied soils could be transformed into a plant-available form. Results suggest that keeping soil P content in the range of 50–80 mg P kg⁻¹ and organic fertilization (and probably also legume cropping) are useful ways of using P from fertilizers or soil reserves. Results also suggest that the Mehlich III soil test brings useful information for P management.

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References

- Alewell, C., B. Ringeval, C. Ballabio, D. A. Robinson, P. Panagos, and P. Borrelli. 2020. Global phosphorus shortage will be aggravated by soil erosion. *Nature Communications* 11 (1):4546. doi:10.1038/s41467-020-18326-7.
- Barrow, N. J., D. Roy, and A. Debnath. 2022. Evaluating the benefits of legacy phosphate. *Plant and Soil* 480 (1–2): 561–70. doi:10.1007/s11104-022-05601-3.
- Bindrabn, P. S., C. O. Dimkpa, and R. Pandey. 2020. Exploring phosphorus fertilizers and fertilization strategies for improved human and environmental health. *Biology and Fertility of Soils* 56 (3):299–317. doi:10.1007/s00374-015-1039-7.
- Blackwell, M., T. Darch, and R. Haslam. 2019. Phosphorus use efficiency and fertilizers: Future opportunities for improvement. *Frontiers of Agricultural Science and Engineering* 6 (4):332–40. doi:10.15302/J-FASE-2019274.
- Buczko, U., M. van Laak, B. Eichler-Löbermann, W. Gans, I. Merbach, K. Panten, E. Peiter, T. Reitz, H. Spiegel, and S. von Tucher. 2018. Re-evaluation of the yield response to phosphorus fertilization based on meta analyses of long-term field experiments. *Ambio* 47 (S1):50–61. doi:10.1007/s13280-017-0971-1.
- Cui, H., W. Sun, M. Delgado-Baquerizo, W. Song, J. Ma, K. Wang, and X. Ling. 2021. Cascading effect of N fertilization activate biologically driven mechanisms promoting P availability in a semi-arid grassland ecosystem. *Functional Ecology* 35 (4):1001–11. doi:10.1111/1365-2435.13773.
- Čapek, P., S. Manzoni, E. Kaštovská, B. Wild, K. Diáková, J. Bárta, J. Schnecker, C. Biasi, P. J. Martikainen, R. J. E. Alves, et al. 2018. A plant-microbe interaction framework explaining nutrient effects on primary production. *Nature Ecology & Evolution* 2 (10):1588–96. doi:10.1038/s41559-018-0662-8.
- Dao, H. T. 2014. Landscape-scale geographic variations in microbial biomass and enzyme-labile phosphorus in manure-amended Hapludults. *Biology and Fertility of Soils* 50 (1):155–67. doi:10.1007/s00374-013-0844-0.
- Hejcmán, M., E. Kunzová, and P. Šrek. 2012. Sustainability of winter wheat production over 50 years of crop rotation and N, P and K fertilizer application on illimerized luvisol in the Czech Republic. *Field Crops Research* 139: 30–8. doi:10.1016/j.fcr.2012.10.005.
- Hallama, M., C. Pekrun, H. Lambers, and E. Kandeler. 2019. Hidden miners – the role of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. *Plant and Soil* 434 (1–2):7–45. doi:10.1007/s11104-018-3810-7.
- Hijbeek, R., H. F. M. ten Berge, A. P. Whitmore, D. Barkusky, J. J. Schröder, and M. K. van Ittersum. 2018. Nitrogen fertilizer replacement values for organic amendments appear to increase with N application rates. *Nutrient Cycling in Agroecosystems* 110 (1):105–15. doi:10.1007/s10705-017-9875-5.
- Hopkins, B. G., K. J. Fernelius, N. C. Hansen, and D. L. Eggett. 2018. AVAIL phosphorus fertilizer enhancer: Meta-analysis of 503 field evaluations. *Agronomy Journal* 110 (1):389–98. doi:10.2134/agronj2017.07.0385.
- Hopkins, B. G., and N. C. Hansen. 2019. Phosphorus management in high-yield systems. *Journal of Environmental Quality* 48 (5):1265–80. doi:10.2134/jeq2019.03.0130.
- Jing, J., Y. Rui, F. Zhang, Z. Rengel, and J. Shen. 2010. Localized application of phosphorus and ammonium improves growth of maize seedlings by stimulating root proliferation and rhizosphere acidification. *Field Crops Research* 119 (2–3):355–64. doi:10.1016/j.fcr.2010.08.005.
- Káš, M., G. Mühlbachová, H. Kusá, and M. Pechová. 2016. Soil phosphorus and potassium availability in long-term field experiments with organic and mineral fertilization. *Plant, Soil and Environment* 62 (12):558–65. doi:10.17221/534/2016-PSE.
- Kautz, T., W. Amelung, F. Ewert, T. Gaiser, R. Horn, R. Jahn, M. Javaux, A. Kemna, Y. Kuzyakov, J. C. Munch, et al. 2013. Nutrient acquisition from arable subsoils in temperate climates: A review. *Soil Biology and Biochemistry* 57:1003–22. doi:10.1016/j.soilbio.2012.09.014.
- Klír, J., E. Kunzová, and P. Čermák. 2008. *Frame methodics of plant nutrition and fertilization*. Vol. 48. Prague: doi:CropResearchInstitute.
- Kulhánek, M., J. Černý, J. Balík, O. Sedlár, and F. Vašák. 2019. Change of bioavailable phosphorus content in the long-term field fertilizing experiment. *Soil and Water Research* 14 (4):240–5. doi:10.17221/175/2018-SWR.
- Ludewig, U., L. Yuan, and G. Neumann. 2019. Improving the efficiency and effectiveness of global phosphorus use: Focus on root and rhizosphere levels in the agronomic system. *Frontiers of Agricultural Science and Engineering* 6 (4):357–65. doi:10.15302/J-FASE-2019275.
- Malarino, A. P. 2003. Field calibration for corn of the Mehlich-3 soil phosphorus test with colorimetric and inductively coupled plasma emission spectroscopy determination methods. *Soil Science Society of America Journal* 67: 1928–34. doi:10.2136/sssaj2003.1928.
- Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis* 15 (12):1409–16. doi:10.1080/00103628409367568.
- Menezes-Blackburn, D., C. Giles, T. Darch, T. S. George, M. Blackwell, M. Stutter, C. Shand, D. Lumsdon, P. Cooper, R. Wendler, et al. 2018. Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: A review. *Plant and Soil* 427 (1):5–16. doi:10.1007/s11104-017-3362-2.

- Mosali, J., K. Desta, R. K. Teal, K. W. Freeman, K. L. Martin, J. W. Lawles, and W. R. Raun. 2006. Effect of foliar application of phosphorus on winter wheat grain yield, phosphorus uptake and use efficiency. *Journal of Plant Nutrition* 29 (12):2147–63. doi:10.1080/01904160600972811.
- Mühlbachová, G., P. Čermák, R. Vavera, T. Lošák, and J. Hlušek. 2016. The effect of phosphorus applications on changes in the soil content of P and yields of barley biomass. *Journal International Scientific Publications* 4: 564–70.
- Sattari, S. Z., A. F. Bouwman, K. E. Giller, and M. K. van Ittersum. 2012. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proceedings of the National Academy of Sciences of the United States of America* 109 (16):6348–53. doi:10.1073/pnas.1113675109.
- Schneider, K. D., J. R. Thiessen Martens, F. Zvomuya, D. K. Reid, T. D. Fraser, D. H. Lynch, I. P. O'Halloran, and H. F. Wilson. 2019. Options for improved phosphorus cycling and use in agriculture at the field and regional scales. *Journal of Environmental Quality* 48 (5):1247–64. doi:10.2134/jeq2019.02.0070.
- Sedlář, O., J. Balík, M. Kulháněk, J. Černý, and M. Kos. 2018. Mehlich 3 extractant used for evaluation of wheat available phosphorus and zinc in calcareous soils. *Plant, Soil and Environment* 64 (2):53–7. doi:10.17221/691/2017-PSE.
- Spohn, M., T. J. Novák, J. Incze, and L. Giani. 2016. Dynamics of soil carbon, nitrogen and phosphorus in calcareous soils after land-use abandonment – A chronosequence study. *Plant and Soil* 401 (1–2):185–96. doi:10.1007/s11104-015-2513-6.
- Tóth, G., R. A. Guicharnaud, B. Tóth, 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. doi:10.1016/j.eja.2013.12.008.
- Von Tucher, S., D. Hörndl, and U. Schmidhalter. 2018. Interaction of soil pH and phosphorus efficacy: Long-term effects of P fertilizer and lime applications on wheat, barley and sugar beet. *Ambio* 47 (S1):41–9. doi:10.1007/s13280-017-0970-2.
- 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 & Technology* 48 (12):6523–30. doi:10.1021/es501670j.
- Wollmann, I., A. Gauro, T. Müller, and K. Möller. 2018. Phosphorus bioavailability of sewage sludge-based recycled fertilizers. *Journal of Plant Nutrition and Soil Science* 181 (2):158–66. doi:10.1002/jpln.201700111.
- Zar, J. H. 2010. *Biostatistical analysis*, 5th ed., 255. Hoboken, NJ: Pearson Prentice Hall.
- Zbíral, J., E. Čizmarová, R. Dočkalová, E. Fojtlová, H. Hájková, H. Holcová, N. Kabátová, E. Niedobová, M. Rychlý, K. Staňková, et al. 2014. *Plant analyses*, 120. Brno: Czech Central Institute for Supervising and Testing in Agriculture.
- Zbíral, J., E. Čizmarová, E. Obdržálková, M. Rychlý, V. Vilamová, J. Srnková, and A. Žalmanová. 2016. Soil analyses. *Part I*. Brno: Czech Central Institute for Supervising and Testing in Agriculture. (in Czech).