

The influence of different intensities of phosphorus fertilizing on available phosphorus contents in soils and uptake by plants

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ABSTRACT

A gradual increase of phosphorus (P) concentrations in combination with organic and mineral fertilizers was applied to clayey soils at six precise experimental field sites with different climatic conditions within the Czech Republic. Soil samples were collected after the harvest of barley. Readily available P concentrations were determined using water and 0.01M CaCl_2 extractions, mobile phosphate contents were determined using the extraction procedures Mehlich 3 and Olsen. Furthermore, P uptake by barley plants was assessed. All selected procedures showed that increasing concentrations of applied P increased the mobile and readily available P contents in soils. Phosphorus uptake by barley plants ranged between 9.00 and 14.5 kg/ha and increased P application resulted in increased P concentrations in plants. Statistical analyses were performed using the Spearman test. The closest relationship was obtained for P uptake by plants and the water extraction ($r = 0.81$). Significant relationships were also obtained for plant uptake and the Mehlich 3 and CaCl_2 methods ($r = 0.40$ and 0.36 , respectively). There was no statistical dependence between P uptake and the Olsen method ($r = 0.25$). Regression analysis was expressed best as linear regression. The closest relationship was found for water extracts and P uptake by plants (with a determination coefficient of 65%). Determination coefficients for P uptake and other methods used were significantly lower (max. 20%).

Keywords: long-term experiments; mobile forms of P; readily available P; plant uptake of P

Almost all phosphorus (P) fractions in soils converted to phosphate ions are taken up by plants. While H_2PO_4^- is the prevailing P form in acidic soils, HPO_4^{2-} is the predominant form in alkaline soils (Mengel 1991, Schilling 2000, Blume et al. 2002). Marschner (1995) found that the contents of the water-extractable P fraction, closely related to yields, reach only 0.8–8.0 mg P/kg. Another fraction influencing P uptake is partially mobile (i.e. exchangeable sorbed) P, which is easily and rapidly released into soil solution (McGechan and Lewis 2002).

Mobile phosphate contents in non-fertilized soils vary significantly (10–100 mg P/kg). The vast majority of P is bound to less soluble soil compounds (Marschner 1995). Tiessen and Moir (1993) showed that it is indispensable to precisely define the availability of P especially for predicting plant uptake.

It is important to note that plant species vary in the ability of taking up P due to different root systems, mycorrhiza and growth speed (Mengel 1991). Another important factor involved in P mobilization are soil microorganisms (Kuono et al. 1995). Due to the fact that available P is consistently supplied by less available P through dissolution, desorption and mineralization of organic P, the level of available P is strongly dependent on specific soil-climatic conditions, the cultivated crop and date of soil sampling (Tiessen and Moir 1993). McGechan and Lewis (2002) found that the determination of P availability is complicated since P applied as mineral fertilizers can be effectively sorbed. At sites fertilized with P, it is possible to observe mobile P in colloid forms and/or bound to soil particles.

There are several methods used for the determination of readily available P, such as the CaCl_2

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Table 1. Characteristics of the studied sites

| Site | Founded in year | Altitude above sea level (m) | Average | | Soil type | pH (CaCl ₂) |
|-----------------|-----------------|------------------------------|--------------------|------------------|------------|-------------------------|
| | | | precipitation (mm) | temperature (°C) | | |
| Jaroměřice | 1975 | 425 | 535 | 7.5 | luvisol | 6.3 |
| Staňkov | 1981 | 370 | 511 | 7.8 | luvisol | 6.0 |
| Vysoká | 1983 | 595 | 655 | 7.4 | pseudogley | 6.3 |
| Sedlec | 1972 | 300 | 581 | 8.4 | chernozem | 7.1 |
| Pusté Jakartice | 1979 | 290 | 650 | 8.0 | luvisol | 5.8 |
| Uherský Ostroh | 1972 | 196 | 551 | 9.2 | luvisol | 6.6 |

extraction (Houba et al. 1994) and the water extraction (Luscombe et al. 1979). Methods for determining mobile P in soils include, among others, the Mehlich 3 (Mehlich 1984) and Olsen (Olsen et al. 1954) procedure.

MATERIAL AND METHODS

Six sites designed for long-term experiments with different climatic conditions were chosen in the Czech Republic (Table 1). The soils are classified as sandy loam. Separate nutrients applied to soils are summarized in Table 2.

Organic fertilizers (40 t manure/year) were applied regularly within crop rotation to root crops (potatoes, sugar beet). Nitrogen was applied during soil preparation before sowing or planting in the form of ammonium sulfate; further fertilization was in the form of ammonium nitrate with lime. The source of P was superphosphate. Potassium was applied as 60% potassium salt.

Soil samples were collected after the harvest of barley (included in the crop rotation system), air-dried and sieved through a 2-mm sieve. Extracts

were analyzed spectrophotometrically using the SKALAR SAN^{PLUS} SYSTEM®.

The standard reference material ISE PER 2003-1, SAMP 1-4 (International Soil-analytical Exchange Programme, University Wageningen, The Netherlands) was used.

In order to determine readily available phosphorus, water extracts (Luscombe et al. 1979) and calcium chloride extracts (Houba et al. 1994) were used.

In order to determine the concentrations of mobile phosphates, the extractions Mehlich 3 (Mehlich 1984) and Olsen (Olsen et al. 1954) were used.

Phosphorus uptake was calculated from plant analyses, main yields and by-products. These data were obtained from the cooperation with CISTA (Central Institute for Supervising and Testing in Agriculture, Brno).

RESULTS AND DISCUSSION

The average yearly P balance was evaluated throughout the whole experiment. Table 3 shows the negative P balance at non-treated variants and

Table 2. Fertilizing system of the precise field experiment (average contents of applied nutrients in kg/ha/year)

| Variant number | Fertilizing variant | Nutrients | | |
|----------------|---|-----------|----|----|
| | | N | P | K |
| 1 | control | 0 | 0 | 0 |
| 2 | manure (to root crops) | 6 | 2 | 9 |
| 3 | N ₂ P ₀ K ₂ (+ manure to root crops) | 64 | 2 | 68 |
| 4 | N ₂ P ₁ K ₂ (+ manure to root crops) | 64 | 24 | 68 |
| 5 | N ₂ P ₂ K ₂ (+ manure to root crops) | 64 | 36 | 68 |
| 6 | N ₂ P ₃ K ₂ (+ manure to root crops) | 64 | 52 | 68 |

Table 3. Long-term balance between P input by fertilization and P output by harvest (average values from all sites throughout the whole experiment)

| Variant number | Fertilizing variant | Average balance (for one site) | |
|----------------|---|--------------------------------|--------------|
| | | (kg/ha) | (kg/ha/year) |
| 1 | control | –458 | –16 |
| 2 | manure (to root crops) | –295 | –10 |
| 3 | N ₂ P ₀ K ₂ (+ manure to root crops) | –396 | –14 |
| 4 | N ₂ P ₁ K ₂ (+ manure to root crops) | 182 | 6 |
| 5 | N ₂ P ₂ K ₂ (+ manure to root crops) | 476 | 17 |
| 6 | N ₂ P ₃ K ₂ (+ manure to root crops) | 904 | 32 |

at variants treated with P in a non-mineral form. The addition of mineral P together with manure to root crops (24 kg P/ha year) resulted in a change of the balance to +6 kg P/ha year (var. 4). Increasing concentrations of P resulted in an increase of the positive balance to +32 kg/ha year (var. 6: N₂P₃K₂ + manure).

In the case of the control variant, the negative P balance of –458 kg P/ha was observed – the application of manure resulted in an increase to –295 (var. 2) and –395 kg P/ha (var. 3). Only the addition of P in mineral form (24 kg/ha) resulted in a positive balance (+182 kg P/ha). The highest balance value (+904 kg P/ha) since the beginning of the experiment was observed at the variant N₂P₃K₂.

Furthermore, changes in contents of different phosphate forms in soils were determined during the experiment. Variants treated with P always resulted in increased P contents in soils. This was the case for both readily available and mobile P. Average contents of readily available P ranged between 3.8 and 9.5 mg P/kg (water extraction) and between 0.2 and 2.8 mg P/kg (0.01M CaCl₂ extraction). The highest water extractable P contents were obtained for the variant N₂P₃K₂ + manure with an average value of 9.5 mg P/kg. This value is still lower (by 7 mg P/kg) than the value reported by Koopmans et al. (2002) for over-fertilized soils in the Netherlands. On the other hand, the lowest results were obtained for the control, where the average content of readily available P reached only 3.8 mg P/kg. This is in accordance with the values of Marschner (1995) who stated that for untreated soils the concentration of water-extractable P reaches only 0.8–8.0 mg P/kg.

The Mehlich 3 protocol proved to be the strongest extraction procedure for the determination of mobile P, with average values from 45 to 112 mg P/kg.

The Olsen extraction procedure resulted in values between 25–55 mg P/kg.

Increasing levels of P fertilizing resulted in increased P uptake by barley plants. The lowest uptake was observed for control variants (9 kg P/ha). The highest values were obtained, as expected, for the N₂P₃K₂ + manure variant, where 52 kg P/ha in average was applied to the soil. In this case, the uptake of P by barley was 14.5 kg P/ha. Increased P uptake by plants after soil-applied P to soils was observed by Schmidt et al. (1997) in long-term experiments with P applied in mineral forms (from 0 to 440 kg P/ha).

The main objective of the study was to specify the relationships between P uptake by plants and P contents in soils as determined by different extraction procedures. Due to relatively high differences between individual sites, it was not possible to perform an analysis of variance and thus test evaluating files. The Spearman test with the level of significance set to $\alpha < 0.05$ was used for correlation analysis.

Linear regression proved to be the best method in regression analysis. Significant relationships between P uptake by barley plants and the CaCl₂ method, water extraction and Mehlich 3 (Table 4) were found. However, a close relationship ($r^2 = 0.82$) was obtained only in the case of the water extraction, even at the level of significance of $\alpha < 0.0001$. This fact was also proved by Luscombe et al. (1979) who studied relationships between P content in soil and plant yields. Relatively good correlations were obtained between P uptake and the methods Mehlich 3 ($r^2 = 0.37$) and the CaCl₂ extraction ($r^2 = 0.34$).

In the case of the Olsen method, the correlation coefficient reached only 0.22, which is not a significant relationship at the set significance level. This method is based on the use of HCO₃[–],

Table 4. Correlations between P uptake and observed methods

| | Mehlich 3 | Olsen | CaCl ₂ | Water extract |
|--|-----------|--------|-------------------|---------------|
| Correlation with P uptake (r^2) | 0.371 | 0.216 | 0.348 | 0.818 |
| The level of significance (α) | 0.0300 | 0.2100 | 0.0400 | 0.0001 |

CO₃²⁻ and OH⁻ ions at pH 8.5 causing thus the precipitation of CaCO₃ and a subsequent release of phosphate ions into the solution. Therefore, this method is the most suitable for soils with high carbonate contents. Nevertheless, it is useable even for more acidic soils, where these ions, together with Fe²⁺ and Al³⁺, form oxyhydroxides (Sims 2000). However, Schoenau and Karamanos (2000) highlight the inaccuracies during the determination of mobile P in these soils using the Olsen method.

The method is further influenced by extraction of an insufficient content of the labile organic fraction, which can play an important role during P uptake by plants (Franzen et al. 1999).

As it was stated before, linear regression was the most suitable form of regression analysis. The relationships between CaCl₂, H₂O extractants and P uptake by plants are summarized in Figure 1. It is evident that the water extraction best correlated with P uptake by plants.

The regression equation can be expressed in the form:

$$P_{\text{uptake}} = 1.11 \times P_{\text{H}_2\text{O}} + 5.20 \quad (1)$$

where: P_{uptake} is uptake of P by plants (kg P/ha) and $P_{\text{H}_2\text{O}}$ is water extractable P (mg P/kg).

The coefficient of determination R^2 indicates that changes in P contents in the water extract can be expressed in 66% as the change in P uptake by plants, which indicates a close relationship between these two parameters. The CaCl₂ method does not correlate well with P uptake. The regression equation can be expressed as:

$$P_{\text{uptake}} = 1.44 \times P_{\text{CaCl}_2} + 11.10 \quad (2)$$

where: P_{CaCl_2} is the amount of P measured in 0.01M CaCl₂ extract (mg P/kg).

The coefficient of determination however shows that P uptake can be expressed only in 13% as the change of P contents in the CaCl₂ extract. This can be caused by the bioavailable phosphate ions forming Ca-P complexes during the extraction that cannot be analyzed (McDowell et al. 2003). This method is thus less accurate. Furthermore, this method is not suitable for conventional agrochemical analyses due to its high time variability (McGechan and Lewis 2002).

Figure 2 shows the relationships between the Mehlich 3/Olsen method and P uptake by plants. Closer relationships were observed between P uptake and contents of mobile phosphates determined by the Mehlich 3 method as it was already

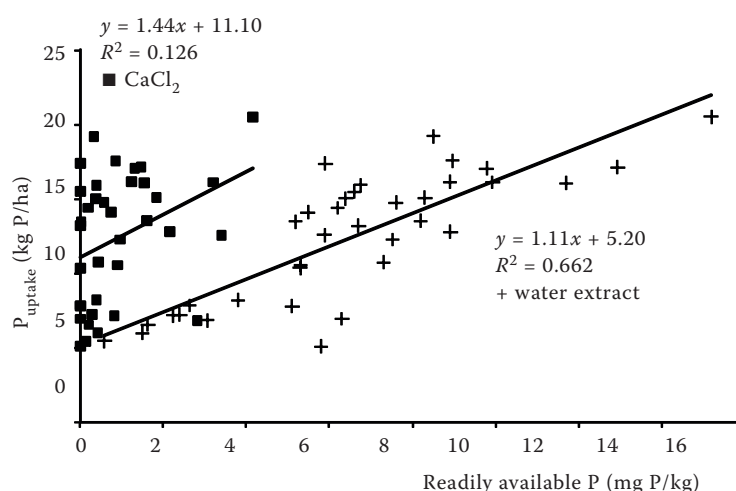


Figure 1. Correlation between P uptake by plants and readily available P in the soil

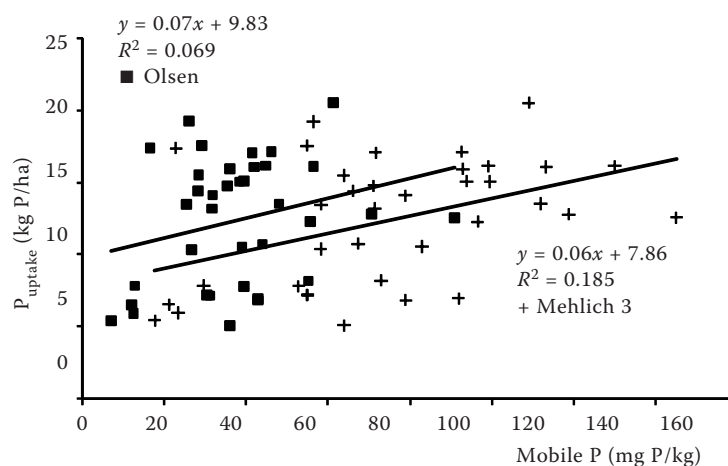


Figure 2. Correlation between P uptake by plants and mobile P in the soil

shown by correlation analyses. The regression equation is as follows:

$$P_{\text{uptake}} = 0.06 \times P_{\text{M3}} + 7.86 \quad (3)$$

where: P_{M3} is the amount of P measured in Mehlich 3 extract (mg P/kg).

The coefficient of determination R^2 was higher than in the case of CaCl_2 , but accounted only for 0.2. This indicates that changes in P uptakes by plants are related to P contents determined by the Mehlich 3 method only in 20%. Even a weaker relationship was obtained for P uptake and the Olsen method.

The coefficient of determination $R^2 = 0.08$ showed that there is almost no relationship between the values obtained from the Olsen method and P uptake by plants. Low coefficients of determination are probably caused by the fact that both methods focus on the determination of mobile phosphates, i.e. P fractions not readily bioavailable.

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