

# THE CONTENT OF AVAILABLE PHOSPHORUS IN SOILS AND P UPTAKE BY PLANTS\*

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Phosphorus (P) uptake and P contents in soils were measured in the topsoil and plant samples taken on six precise field experiments with different climatic conditions. Phosphorus concentrations were determined using water, 0.01M CaCl<sub>2</sub>, Mehlich 3 and anion exchange membranes (AEM) methods. All selected procedures showed that with increasing doses of applied P increased the mobile and readily available P contents. Correlation analysis was 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 AEM, Mehlich 3 and CaCl<sub>2</sub> methods ( $r = 0.44, 0.40$  and  $0.36$ , respectively). Regression analysis between P uptake and selected methods was expressed best as linear regression. Determination coefficient ( $R^2$ ) for P uptake and water extract was 0.66. The coefficients with other methods used were significantly lower (max. 0.20).

Mehlich 3; AEM; water extract; 0.01 M CaCl<sub>2</sub> extract; P balance; plant uptake of P

## INTRODUCTION

Almost all phosphorus (P) fractions in soils, converted to phosphate ions, are taken up by plants. While H<sub>2</sub>PO<sub>4</sub><sup>-</sup> is the prevailing P species in acidic soils, HPO<sub>4</sub><sup>2-</sup> is the predominant species in alkaline soils (Blum et al., 2002; Mengel, 1991; Schilling, 2000).

The P content in soil solution is usually low compared to total P content. This fraction is possible to estimate with water extract (Luscombe et al., 1979) or with 0.01M CaCl<sub>2</sub> (Houba et al., 1994). The content of P in soil solution ranges between 0.80–8.00 mg P.kg<sup>-1</sup> (Marschner, 1995). Koopmans et al. (2002) determined in average 16.0 mg P.kg<sup>-1</sup> in 151 samples of overfertilized soils. These fractions should correlate well with plant uptake.

Exchangeable sorbed P (P<sub>ex</sub>) is another important source of bioavailable P. It is the part of soil P that is exchangeable and sorbed on the surface of soil particles. It can be easily released to the soil solution and become bioavailable. This fraction is possible to estimate for example with anion resins (Lewis, McGeehan, 2002; Tiessen, Moir, 1993), or recently, via anion exchange membranes (AEM) (Schoenau, Huang, 1991; Kuono et al., 1995; Sato, Comerford, 2006).

The most commonly methods used are those for estimating total bioavailable P in soils: e.g., Mehlich 3 (Mehlich, 1984), Olsen (Olsen et al., 1954), CAL and Doppel-Lactat (DL) (Hoffman, 1991), Bray 1 and 2 (Bray, Kurtz, 1945) etc. These extractions are focused on the determination of potentially quickly bioavailable P. It means phosphorus in soil solution and weakly bound phosphorus.

Total bioavailable phosphate contents in non-fertilized soils vary significantly (10–100 mg P.kg<sup>-1</sup>). The vast ma-

jority of P is bound in 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, root exudates, mycorrhiza and growth speed (Mengel, 1991). Another important factor involved in P mobilization are soil microorganisms (Kuono et al., 1995) and soil and climatic conditions (Tiessen, Moir, 1993).

The aim of this work was to compare the P content in soil solution and the content of bioavailable P with P uptake by plants, using 0.01M CaCl<sub>2</sub> extraction (Houba et al., 1994), water extraction (Luscombe et al., 1979), AEM (Kuono et al., 1995) and the Mehlich 3 (Mehlich, 1984) procedure.

## MATERIAL AND METHODS

Six sites of long term field experiments with different climatic conditions were chosen in the Czech Republic (Table 1). The soils are classified as loamy. Nutrients applied to soils are summarized in Table 2.

Organic fertilizers (40 t manure year<sup>-1</sup>) 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.

Topsoil (0–30 cm) samples were collected after the harvest of barley (included in the crop rotation) in the year 2003, air dried and sieved through a 2-mm sieve. Extracts

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Table 1. Characteristic of the studied sites

Site	Founded in year	Altitude above sea level (m)	Average		Soil type	pH (CaCl <sub>2</sub> )
			precipitation (mm)	temperature (°C)		
Jaroměřice	1975	425	535	7.50	luvisol	6.30
Staňkov	1981	370	511	7.80	luvisol	6.00
Vysoká	1983	595	655	7.40	pseudogley	6.30
Sedlec	1972	300	581	8.40	chernozem	7.10
Pusté Jakartice	1979	290	650	8.00	luvisol	5.80
Uherský Ostroh	1972	196	551	9.20	luvisol	6.60

Table 2. Fertilizing system of the precise field experiment (average contents of applied nutrients, in kg.ha<sup>-1</sup>.year<sup>-1</sup>)

Variant no.	Fertilizing variant	Nutrients		
		N	P	K
1	control	0	0	0
2	manure (to root crops)	6	2	9
3	N <sub>2</sub> P <sub>0</sub> K <sub>2</sub> (+ manure to root crops)	64	2	68
4	N <sub>2</sub> P <sub>1</sub> K <sub>2</sub> (+ manure to root crops)	64	24	68
5	N <sub>2</sub> P <sub>2</sub> K <sub>0</sub> (+ manure to root crops)	64	36	0
6	N <sub>2</sub> P <sub>2</sub> K <sub>2</sub> (+ manure to root crops)	64	36	68
7	N <sub>2</sub> P <sub>3</sub> K <sub>2</sub> (+ 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 no.	Fertilizing variant	Average balance (for one site)	
		kg.ha <sup>-1</sup>	kg.ha <sup>-1</sup> .year <sup>-1</sup>
1	control	-458	-16.0
2	manure (to root crops)	-396	-14.0
3	N <sub>2</sub> P <sub>0</sub> K <sub>2</sub> (+ manure to root crops)	-396	-14.0
4	N <sub>2</sub> P <sub>1</sub> K <sub>2</sub> (+ manure to root crops)	182	6.00
5	N <sub>2</sub> P <sub>2</sub> K <sub>0</sub> (+ manure to root crops)	476	17.0
6	N <sub>2</sub> P <sub>2</sub> K <sub>2</sub> (+ manure to root crops)	476	17.0
7	N <sub>2</sub> P <sub>3</sub> K <sub>2</sub> (+ manure to root crops)	904	32.0

Table 4. Correlations between P uptake and observed methods

	Mehlich 3	AEM	CaCl <sub>2</sub>	Water extract
Correlation with P uptake ( <i>r</i> )	0.37	0.44	0.35	0.82
<i>p</i> -value	0.03	0.01	0.04	0.0001

were analyzed spectrophotometrically using SKALAR SAN<sup>PLUS</sup> SYSTEM<sup>®</sup>.

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 (L u s c o m b e et al., 1979) and 0.01M calcium chloride extracts (H o u b a et al., 1994) were used.

In order to determine the concentrations of mobile phosphates, the extractions Mehlich 3 (M e h l i c h, 1984) and AEM (modified after K u o n o et al., 1995) were used.

Phosphorus uptake was calculated from plant analyses, yields of main and by-products. These data were obtained from the cooperation with Central Institute for Supervising and Testing in Agriculture, Brno (CISTA), the owner and coordinator of the experimental sites. Correlation analysis were performed using SAS (SAS, 1990) system.

## RESULTS AND DISCUSSION

The average yearly P balance was evaluated throughout the whole experiment. Table 3 shows the negative

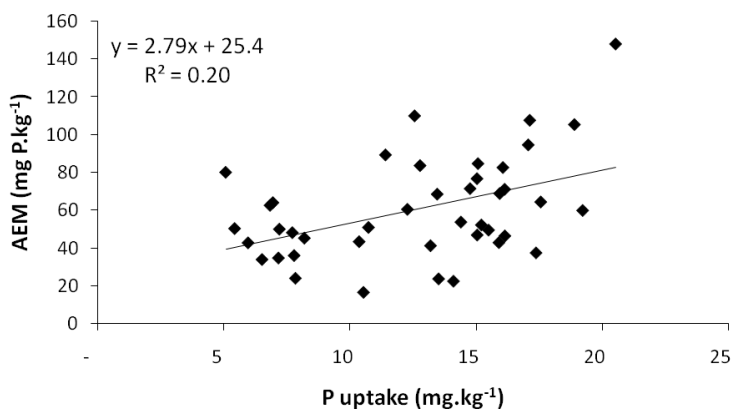


Fig. 1. Correlation between P uptake by plants and AEM method in the soil

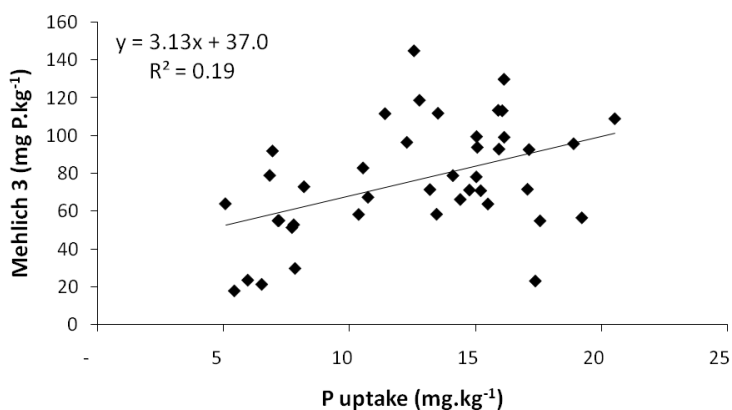


Fig. 2. Correlation between P uptake by plants and Mehlich 3 method in the soil

P balance at non-treated variant and at variant treated with P in a non-mineral form. The addition of mineral P together with manure to root-crops ( $24 \text{ kg P.ha}^{-1} \cdot \text{year}^{-1}$ ) resulted in a change of the balance to  $+6 \text{ kg P.ha}^{-1} \cdot \text{year}^{-1}$  ( $\text{N}_2\text{P}_1\text{K}_2 + \text{manure}$ ). Increasing of the P doses resulted in an increase of the positive balance to  $+32 \text{ kg.ha}^{-1} \cdot \text{year}^{-1}$  ( $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$ ).

In the case of the control variant, the negative P balance of  $-458 \text{ kg P.ha}^{-1}$  was observed – the application of manure resulted in an increase to  $-395 \text{ kg P.ha}^{-1}$  (var. manure and  $\text{N}_2\text{P}_0\text{K}_2 + \text{manure}$ ), respectively. Only the addition of P in mineral form ( $24 \text{ kg P.ha}^{-1}$ ) resulted in a positive balance ( $+182 \text{ kg P.ha}^{-1}$ ). The highest balance value ( $+904 \text{ kg P.ha}^{-1}$ ), since the beginning of the experiment, was observed at the variant  $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$ .

Furthermore, changes in contents of different phosphate forms in soils were determined. Variants treated with P always resulted in increased P contents in soils. This was the case for both the readily available and mobile P. Average contents of readily available P ranged between  $3.80$  (control) and  $9.50$  ( $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$ )  $\text{mg P.kg}^{-1}$  (water extraction) and between  $0.20$  (control) and  $2.80$  ( $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$ )  $\text{mg P.kg}^{-1}$  ( $\text{CaCl}_2$  extraction). The highest water extractable P contents were obtained for the variant  $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$  with an over mentioned average value of  $9.50 \text{ mg P.kg}^{-1}$ . This value is still lower (by  $6.50 \text{ mg P.kg}^{-1}$ ) 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  $3.80 \text{ mg P.kg}^{-1}$ . This is in accordance with the values of Mar-

schner (1995) who stated that for untreated soils the concentration of water-extractable P reaches only  $0.80\text{--}8.00 \text{ mg P.kg}^{-1}$ .

The Mehlich 3 protocol proved to be the strongest extraction procedure for the determination of mobile P, with the median of  $72.0 \text{ mg P.kg}^{-1}$  and the average contents varied from  $45.0 \text{ mg P.kg}^{-1}$  (control) to  $112 \text{ mg P.kg}^{-1}$  ( $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$ ). The median of AEM extraction procedure resulted in  $53.0 \text{ mg P.kg}^{-1}$  and the average contents varied from  $40.0 \text{ mg P.kg}^{-1}$  (control) to  $93.0 \text{ mg P.kg}^{-1}$  ( $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$ ).

Increasing the levels of P fertilizing resulted in increased P uptake by barley plants. The lowest uptake was observed for control variants ( $9 \text{ kg P.ha}^{-1} \cdot \text{year}^{-1}$ ). The highest values were obtained, as expected, for the  $\text{N}_2\text{P}_3\text{K}_2 + \text{manure}$  variant, where  $52 \text{ kg P.ha}^{-1} \cdot \text{year}^{-1}$  in average was applied to the soil. In this case, the uptake of P by barley was  $14.5 \text{ kg P.ha}^{-1} \cdot \text{year}^{-1}$ . Increased P uptake by plants after soil-applied P was observed by Schmidt et al. (1997) in long-term experiments with P applied in mineral form (from 0 to  $440 \text{ kg P.ha}^{-1}$ ).

The other 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 the relatively high differences between sites, it was not possible to perform analysis of variance and thus tests evaluating files, which did not fulfill the normal distribution, were used. The Spearman test with the level of significance set to  $p$ -value 0.05 was used for correlation analysis.

Significant correlations between P uptake by barley plants and the  $\text{CaCl}_2$  method, water extraction and Meh-

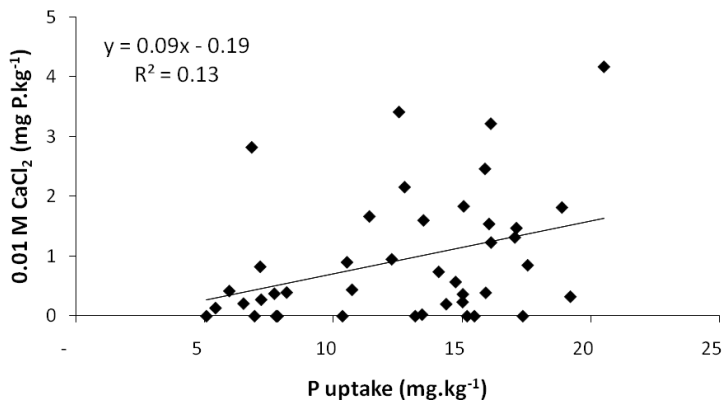


Fig. 3. Correlation between P uptake by plants and 0.01M CaCl<sub>2</sub> extractable P in the soil

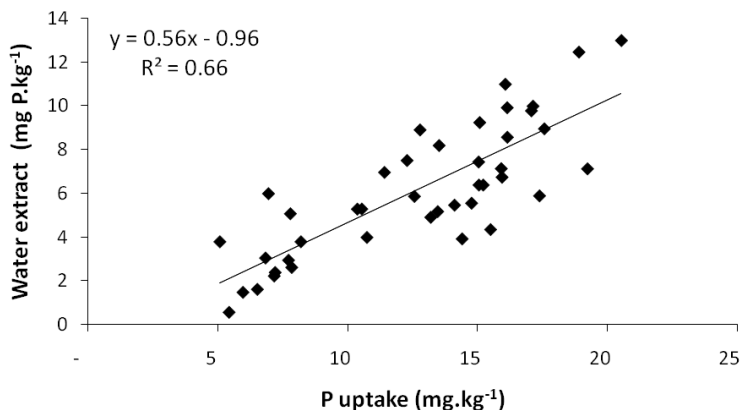


Fig. 4. Correlation between P uptake by plants and water extractable P in the soil

lich 3 (Table 4) were found. However, only in the case of the water extraction a close relationship ( $r = 0.82$ ) was obtained, even at  $p$ -value of 0.0001. This fact was also proved by Luscombe et al. (1979) who studied relationships between P content in soil and plant yields. Relatively weak correlations were obtained between P uptake and the methods AEM ( $r = 0.44$ ), Mehlich 3 ( $r = 0.37$ ) and 0,01M CaCl<sub>2</sub> extraction ( $r = 0.34$ ). There were found big differences between experimental sites. For example at Pusté Jakartice site was not observed the significant relation between P uptake and AEM ( $r = -0.17$ ), Mehlich 3 ( $r = 0.01$ ) method, respectively. However, there were found very close correlations at the Vysoká site (P uptake : Mehlich 3 –  $r = 0.88$ , P uptake : AEM –  $r = 0.81$ ). These differences caused relatively low results of common correlation coefficients.

Linear regression proved to be the best suiting method in regression analysis. Fig. 1 and Fig. 2 shows the regression relationships between the AEM and Mehlich 3 methods and P uptake by plants.

Weak relationship was obtained for P uptake and the AEM method. The coefficient of determination  $R^2 = 0.20$  showed that there is almost no relationship between the values obtained from the AEM method and P uptake by plants.

Similar relationships were observed between P uptake and contents of mobile phosphates determined by the Mehlich 3 method as it was already shown by correlation analyses.

The  $R^2$  was accounted for only 0.19. Low coefficients of determination are probably caused by the fact that both methods are focused on the determination of mobile phosphates, i.e., P fractions not readily bioavailable (McGe-

chan, 2002). The similar results reached Blume et al. (2002), who compared the relative harvest with the results reached with CAL and DL methods.

The relationships between CaCl<sub>2</sub>, water extractants and P uptake by plants are summarized in Figs 3 and 4. The CaCl<sub>2</sub> method does not correlate well with P uptake. The coefficient of determination however shows that P uptake can be expressed only from 13% as the change of P contents in the CaCl<sub>2</sub> extract. This can be caused by the fact that bioavailable phosphate ions form Ca-P complexes during the extraction that cannot be spectrophotometrically analyzed (McDowell et al., 2003). This method is thus less accurate. Furthermore, this method is not suitable for conventional agrochemical analyses due to high variability of data reached in different terms of samples uptake (McGechan, Lewis, 2002).

It is evident that the water extraction best correlated with P uptake by plants. The  $R^2 = 0.66$  indicated a close relationship between these two parameters. This method also after Tieszen and Moir (1993) estimate the P in soil solution and therefore should correlate well with plant uptake.

## CONCLUSIONS

The positive P balance in the soil was reached after adding 24 kg P.ha<sup>-1</sup>.year<sup>-1</sup> and more. The closest correlation coefficients were reached between the water extractable P in soil and P uptake by plants. The correlations between P uptake and results from CaCl<sub>2</sub>, Mehlich 3 and AEM extractions were significant only at the lower  $p$ -values 0.04; 0.03 and 0.01, respectively. The similar trends were obtained with the regression analysis.

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### Obsah přístupného fosforu v půdě a odběr P rostlinami.

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Na šesti stanovištích přesného polního pokusu se středními půdami v různých klimatických podmínkách byl měřen odběr fosforu rostlinami a obsah přístupného fosforu (P) v půdě. Pro stanovení fosforu byl využit vodný výluh, výluh v 0,01 M CaCl<sub>2</sub>, extrakce Mehlich 3 a membrány se zakotveným iontoměničem (AEM). Se vzrůstajícími dávkami P v aplikovaných hnojivech vzrůstaly i obsahy sledovaných forem fosforu. Cílem pokusu bylo hodnocení vztahu mezi odběrem P rostlinami a obsahem P v půdě stanoveným uvedenými metodami. Korelační analýza byla provedena Spearmanovým testem. Nejtěsnější vztah byl nalezen mezi odběrem P rostlinami a obsahem P stanoveným ve vodném výluhu ( $r = 0,81$ ). Signifikantní vztahy byly rovněž pozorovány mezi odběrem P rostlinami a metodami AEM, Mehlich 3 a CaCl<sub>2</sub> ( $r = 0,44$ , 0,40 a 0,36). Pro regresní analýzu se jako nejvýhodnější ukázala lineární regrese. Nejtěsnější vztah byl stejně jako u korelační analýzy vypočten mezi vodným výluhem a odběrem P rostlinou (koeficient determinace 65 %). Koeficienty determinace mezi odběrem P a ostatními metodami byly výrazně nižší (do 20 %).

Mehlich 3; AEM; vodný výluh; výluh 0.01 M CaCl<sub>2</sub>; balance P; odběr P rostlinami

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