doi: 10.17221/534/2016-PSE

Soil phosphorus and potassium availability in long-term field experiments with organic and mineral fertilization

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ABSTRACT

The effect of organic, mineral and combined organic and mineral fertilization of soils on the winter wheat yields and nutrient contents in soils was evaluated in long-term field experiments. Two sites with different soil characteristics were evaluated – Lukavec u Pacova (cambisol) and Ivanovice na Hané (degraded chernozem). The type of fertilization influenced wheat yields. Nutrient uptake by winter wheat was higher under nitrogen (N) fertilization, which resulted in a negative balance of phosphorus (P) and potassium (K) and to a decrease of nutrient contents in the more fertile soils at Ivanovice na Hané. Two soil tests (Mehlich 3 method and NH_4-acetate method) were used to determine P and K availability. The mineral nitrogen fertilization negatively and significantly affected NH_4-acetate extractable concentrations of nutrients in the soils and these were lower in comparison with concentrations of P and K determined by Mehlich 3 method. Relative availability of P in alkaline soils from Ivanovice treated with mineral N increased while the soil pH decreased.

Keywords: Mehlich 3 soil test; NH_4-acetate soil test; *Triticum aestivum*; nutrition; macronutrient; nutrient availability

Long-term field experiments provide one of the means of measuring sustainable management systems in agriculture (Rasmussen et al. 1998) as they contribute to better understanding of the effects of soil fertilization on nutrient availability and crop yields. Long-term fertilization using either organic manure or mineral fertilizer has significant effects on improving crop yields (Lin et al. 2015).

The yields of winter wheat increase depending on the applied mineral nitrogen (N) dose particularly in areas with unfavourable soil-climatic conditions (Káš et al. 2010). Bischoff (1995) showed that combined mineral and organic fertilization increased crop yields more than mineral treatments only. Organic fertilization affects the crop yields more in light loamy-sandy soils due to easier soil warming, increase of microbial activity, better air exchange and, as a consequence, a better release of nutrients contained in organic fertilizers (Hohenmeier et al. 2001).

Phosphorus (P) is the most important nutrient element (other than nitrogen) limiting agricultural production in most regions of the world (Holford 1997). Phosphorus in soils is divided to different fractions with different availability for plants (Kulhánek et al. 2009). Takahashi and Anwar (2007) conducted a 23-year long field experiment applying P fertilization. While the total content of mineral P increased, the increase of available P in the treated plots was only modest. P fertilization was found to be critical for grain yield since the N and K treatment did not increase yield compared with zero treatment (Takahashi and Anwar 2007). According to Takahashi and Anwar (2007) total inorganic P (P_i) and Ca-P_i + Al-P_i + Fe-P_i, increased in the treatments with P application at 0–15 cm. Total P_i was greater at 0–15 cm depth than at 30–50 cm depth. On the other hand, Vanden Nest et al. (2015) showed that zero P-fertilizer application led to a significant decrease in soil P availability and also P leaching was observed during 4-year experimental period. Among organic fertilizers, Kulhánek et al. (2014) found farmyard manure (FYM) to be a good source of phosphorus.

Supported by the Ministry of Agriculture of the Czech Republic, Project No. RO 0416.

doi: 10.17221/534/2016-PSE

Soil potassium (K) supply is one of the main determinant nutrients of the grain yield. The K availability and utilization by plants is partly related to clay content in the soil, but more to the cation exchange surfaces associated with both mineral and organic constituents and also to the capacity of clay minerals to fix K (Blake et al. 1999). Where plant-available soil extractable K supply is insufficient to sustain the maximum growth rate, an asymptotic grain yield response is usually observed as a result of increased K fertilization (Brennan and Bolland 2007). Slowly and readily available forms of K represent the pools important for K supply for crops. Moody and Bell (2006) showed that the following pools were in sequential equilibrium: solution K, exchangeable K, fast release fixed K, and slow release fixed K. The exchangeable K was correlated with K uptake by plants.

The objectives of our research were: (1) to investigate the effects of mineral, organic and combinations of mineral and organic fertilizers on the yields of winter wheat and on the availability of K and P in soils; (2) to evaluate changes in nutrient availability caused by long-term soil fertilization using two soil tests Mehlich 3 and NH_4-acetate.

MATERIAL AND METHODS

Field experiment. The international permanent organic nitrogen long-term field experiment with organic, mineral and combined organic and mineral fertilization (IOSDV – Der Internationale Organische Stickstoffdauerdüngsversuch) – was founded in the year 1984 at two different sites: Lukavec u Pacova and Ivanovice na Hané (Table 1). The experimental treatments were following: (1) C – control; (2) PK – mineral fertilization P and K; (3) NPK – mineral fertilization NPK; (4) FYM – farmyard manure; (5) FYM-PK – farmyard manure + PK; (6) FYM-NPK – farmyard manure + NPK. Mineral fertilizers (P, K, NPK) were applied annually (120 kg N/ha, 35 P kg/ha and 83 K kg/ha), FYM in a dose 30 t/ha once per three years before potato planting. The total dose of nutrients applied to potatoes in crop rotation with FYM was 129 kg N/ha, 51 kg P/ha and 138 kg K/ha, respectively. The crop rotation was following: potatoes, winter wheat, spring barley. The straw after harvest was taken from all experimental plots. The total area of plots was 40 m^2 (5 × 8 m); harvesting area was 18 m^2 (3 × 6 m). Each treatment had three replicates. Treatments with mineral and organic fertilization were concentrated in blocs shifted for every replication in order to change its vertical and horizontal position.

Soil and plant sampling. The soils and plants were sampled at time of winter wheat (cv. Cubus) harvest from two opposite parts of each experimental plot within the years 2010–2014. 4 × 0.5 m of winter wheat row was taken from each plot. The straw and grain yields were determined from partial plant samplings carried out before harvesting and weighing separately the straw and threshed grain.

8 soil cores of diameter 2.5 cm and depth 0–30 cm were sampled from each experimental plot from the same place as the plants were taken. After that, the soils were air-dried and sieved at 2 mm before analysis.

Laboratory analysis. Exchangeable nutrient contents were determined by NH_4-acetate method (Matula 2007). NH_4-acetate method was chosen due to its advantages, among them there is usually a good relationship between readily available elements and plant uptake and the possibility to determine many elements in one extract. Briefly, 5 g of soil was extracted in 100 mL of 0.5 mol/L ammonium acetate and 0.005 mol/L ammonium fluoride, pH = 7. The soils with 0.5 mol/L ammonium acetate were left for 16 h, thereafter they were shaken manually 4 times before filtration.

Total bioavailable nutrients were evaluated by Mehlich 3 method (0.2 mol/L CH_3COOH,

Table 1. Basic characteristics of soils at experimental sites

	Lukavec u Pacova	Ivanovice na Hané
Altitude (m a.s.l.)	620	225
Soil type	cambisol	degraded chernozem
Soil texture	loamy-sandy	loamy
Average precipitation (mm)	633	558
Average temperature (°C)	558	9.4
pH_{CaCl_2}	6.2	7.1
Available nutrients Mehlich 3 (mg/kg)		
P	126	131
K	217	406
Mg	125	211
Ca	1624	3389

doi: 10.17221/534/2016-PSE

0.015 mol/L NH_4F, 0.013 mol/L HNO_3, 0.25 mol/L NH_4NO_3, 0.001 mol/L EDTA) in ratio w:v – 1:10 (10 g of soil and 100 mL of extractant), 10 min shaking and subsequent filtration (Mehlich 1984).

Concentrations of K and P in the straw and grain of winter wheat were determined after digestion in conc. HNO_3, 30% H_2O_2 using the microwave Milestone 1200 system (Connecticut, USA). Thereafter, all soil and plant extracts were determined by the ICP-OES Thermo Jarrel Ash (Nebrasca, USA). The overall uptake of nutrients was calculated from the obtained yields and the P and K contents in the straw and grain.

pH determination. The soil pH was determined in the distilled water extract of 1 mol/L KCl using the ratio 1:2.5 w:v (20 g soil/50 g water). The soil samples were shaken on an overhead shaker for 1 h and then left to equilibrate for 20 h. The suspension was then agitated for 10 min and the pH was measured immediately using a pH meter WTW 315i/SET (Weilheim, Germany).

Statistical analysis. The results from the five-year observations (2010–2014) were statistically analysed using the Statistica 12.0 software (Tulsa, USA). The one-way ANOVA and Tukey's tests were used to determine significant differences among the data. The same characters over histograms in the figures represent statistically identical values of the examined treatments.

RESULTS

Winter wheat yields. The average yields of winter wheat were higher at Ivanovice then at Lukavec site. The medium winter wheat yields at Lukavec according to ANOVA test increased significantly ($P \leq 0.001$) in the following order: control = PK < FYM-PK = FYM < NPK < FYM-NPK (Figure 1). The medium winter wheat yields at Ivanovice increased significantly ($P < 0.01$) as follows: control = PK ≤ FYM = FYM-PK ≤ FYM-NPK = NPK (Figure 1). At Lukavec, the highest yields were obtained for FYM-NPK treatment. At Ivanovice the highest winter wheat yields were obtained using mineral N fertilization without significant difference between NPK and FYM-NPK treatments (Figure 1).

Winter wheat nutrient uptake. The overall winter wheat uptake of K and P differed among treatments significantly at Lukavec ($P \leq 0.001$). The winter wheat uptake of K and P in soils from Ivanovice was less statistically significant ($P \leq 0.05$). The lowest uptake of nutrients was observed in the control and PK treatments in both soils and the highest uptake was obtained for FYM-NPK and NPK treatments (at Ivanovice soils, this was not statistically significant) (Table 2).

K in soils. The average concentrations of potassium in soils determined by Mehlich 3 and NH_4-acetate methods differed significantly among treatments at both experimental sites ($P \leq 0.001$) (Figure 2). The average K concentrations determined by both methods – Mehlich 3 (K_{M3}) and NH_4-acetate ($K_{NH4\text{-}ac}$) in the soils from Ivanovice were higher in comparison with the soils from Lukavec. The organic fertilization increased K contents at Ivanovice soils almost twice in comparison with the mineral fertilization. Significantly lower K concentrations were found for control and NPK treatments in the soils from Lukavec, while the

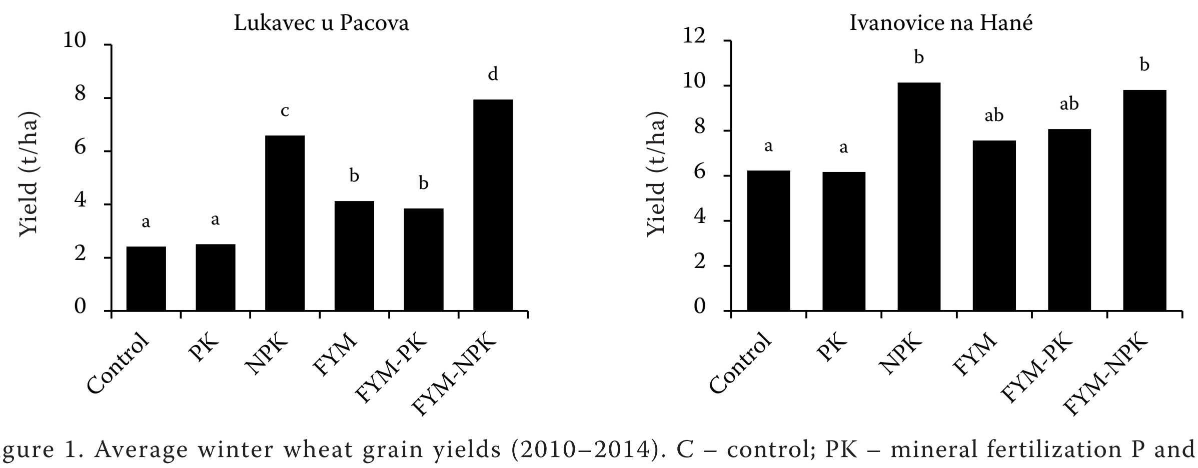

Figure 1. Average winter wheat grain yields (2010–2014). C – control; PK – mineral fertilization P and K; NPK – mineral fertilization NPK; FYM – farmyard manure; FYM-PK – farmyard manure + PK; FYM-NPK – farmyard manure + NPK. The same characters represent statistically identical values of the examined treatments

doi: 10.17221/534/2016-PSE

Table 2. Annual dose of organic and mineral fertilizers (kg/ha), export of phosphorus (P) and potassium (K) by grain and straw of winter wheat in the field experiment

Treatment	Dose of fertilizers		Lukavec u Pacova		Ivanovice na Hané	
	K	P	K	P	K	P
Control	0	0	29.1^{a}	13.7^{a}	71.9^{a}	25.7^{a}
PK	83	35	29.1^{a}	14.1^{a}	65.2^{a}	26.6^{a}
NPK	83	35	81.3^{c}	27.5^{bc}	113.2^{c}	38.8^{b}
FYM	0	0	51.6^{b}	21.9^{b}	77.2^{b}	31.8^{b}
FYM-PK	129	52	45.3^{b}	19.3^{b}	84.3^{b}	33.5^{b}
FYM-NPK	129	52	112.2^{d}	33.5^{c}	130.2^{d}	40.7^{c}

C – control; PK – mineral fertilization P and K; NPK – mineral fertilization NPK; FYM – farmyard manure; FYM-PK – farmyard manure + PK; FYM-NPK – farmyard manure + NPK. The same characters represent statistically identical values of the examined treatments

highest K concentrations were found for FYM-PK treatment. K concentrations in the soils using FYM-NPK treatment were lower in comparison with FYM-PK, however no clear statistical significance was noted. The ratio between the exchangeable and the total bioavailable potassium K_{NH4-ac}/K_{M3} was not significantly affected by treatment in soils from any site (Figure 4).

P in soils. The phosphorus concentrations using Mehlich 3 (P_{M3}) and NH_4-acetate (P_{NH4-ac}) methods in the soils of both experimental sites were significantly affected by the treatment

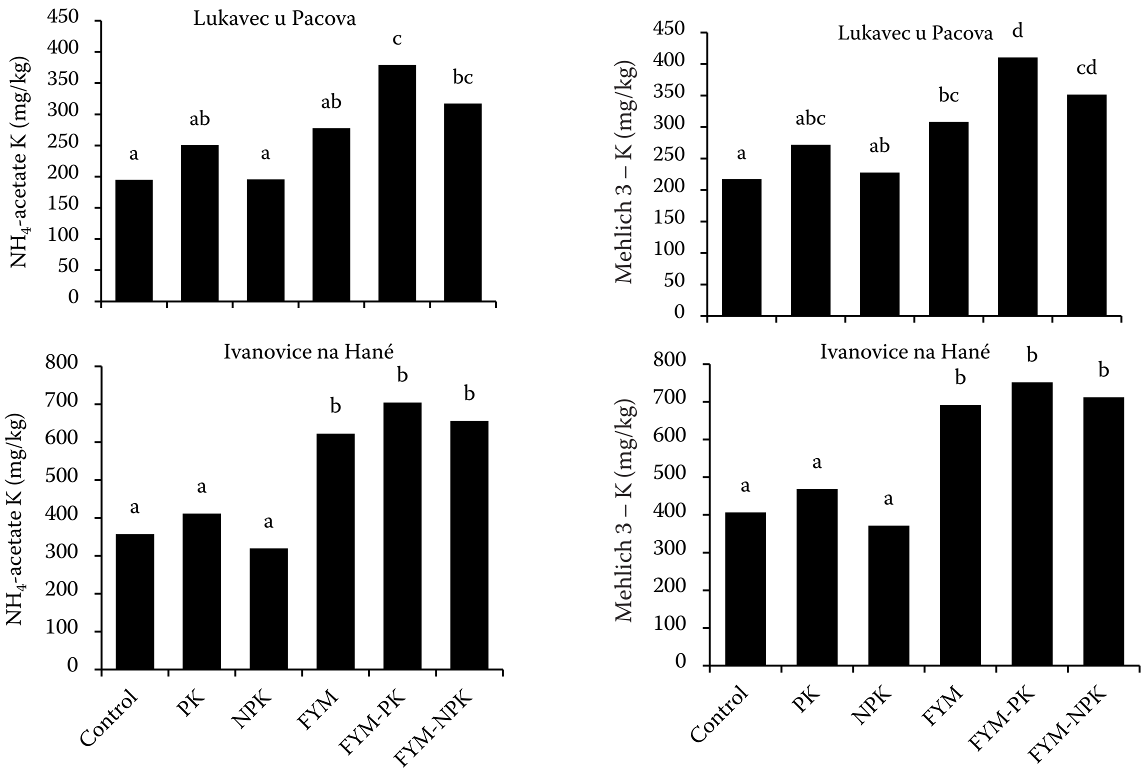

Figure 2. Average NH_4-acetate and Mehlich 3 concentrations of potassium (K) in soils (2010–2014). C – control; PK – mineral fertilization P and K; NPK – mineral fertilization NPK; FYM – farmyard manure; FYM-PK – farmyard manure + PK; FYM-NPK – farmyard manure + NPK. The same characters represent statistically identical values of the examined treatments

doi: 10.17221/534/2016-PSE

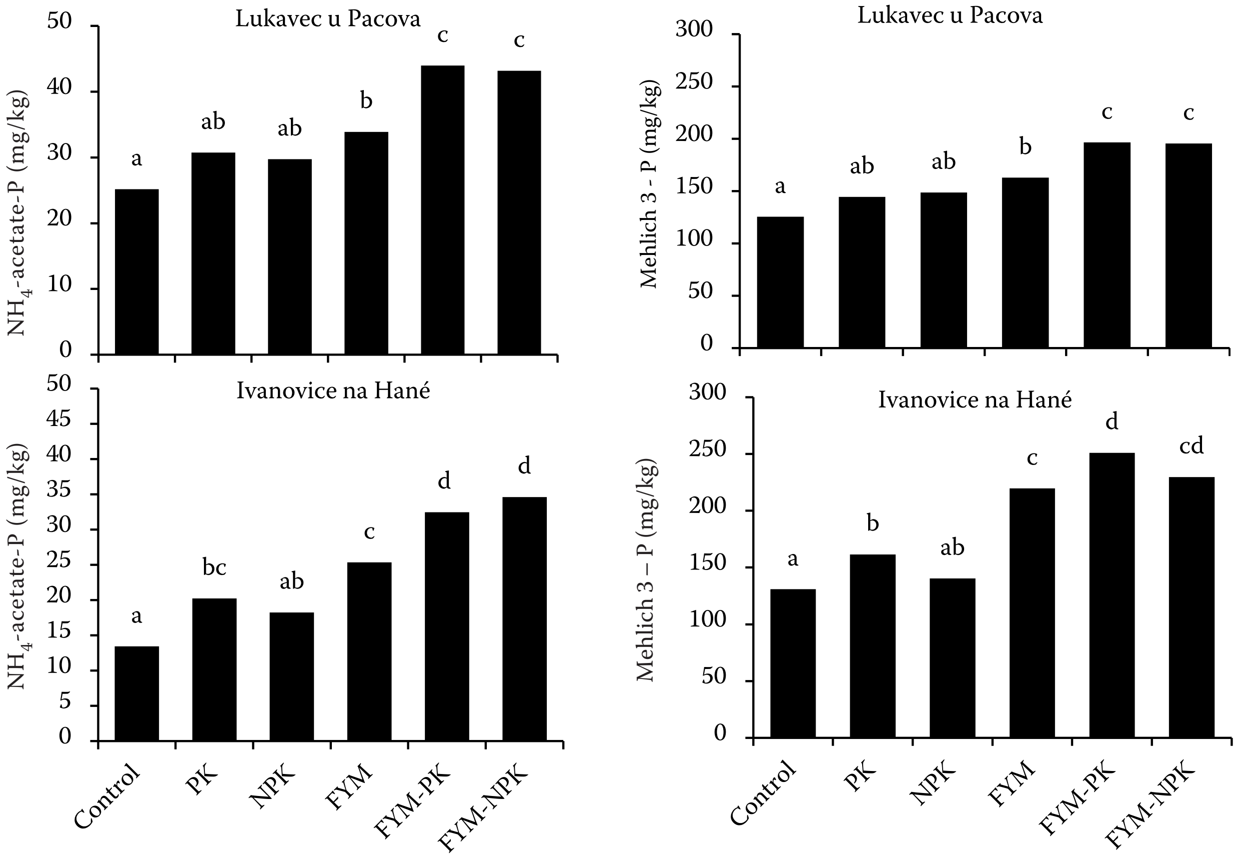

Figure 3. Average NH_4-acetate and Mehlich 3 concentrations of phosphorus (P) in soils (2010–2014). C – control; PK – mineral fertilization P and K; NPK – mineral fertilization NPK; FYM – farmyard manure; FYM-PK – farmyard manure + PK; FYM-NPK – farmyard manure + NPK. The same characters represent statistically identical values of the examined treatments

($P \leq 0.001$) (Figure 3). The lowest P concentrations were found for control soils at both sites and by both methods. The increase in P concentrations was noted using FYM treatments, the FYM-PK and FYM-NPK treatments reached the highest P concentrations. The ratio $P_{NH4\text{-}ac}/P_{M3}$ was significantly affected by treatment at both sites ($P \leq 0.001$). The lowest $P_{NH4\text{-}ac}/P_{M3}$ for soils from Lukavec was noted using NPK treatment and the highest $P_{NH4\text{-}ac}/P_{M3}$ was noted in PK and FYM-PK treatments. There was an increasing trend in ratio $P_{NH4\text{-}ac}/P_{M3}$ from control to NPK and from FYM to FYM-NPK treatments in soils at Ivanovice (Figure 4).

Soil pH. The soil pH determined in H_2O and 1 mol/L KCl was higher in the Ivanovice soils (degraded chernozem) in comparison with the soils from Lukavec (Table 3). The soil pH in soils of both sites was affected by soil treatment ($P \leq 0.001$). The highest pH values were found in control treatments, the lowest pH was found in treatments receiving mineral nitrogen without any significant difference between mineral or organic fertilization. Positive correlations ($P \leq 0.05$; $r = 0.41$) were obtained between K concentrations and pH in the soils from Lukavec, a negative correlation ($P \leq 0.05$, $r = -0.37$) was found between P and pH in soils from Ivanovice.

DISCUSSION

The soils at Lukavec having lower nutrients content than degraded chernozem at Ivanovice reached on average lower yields. A significant increase ($P \leq 0.001$) of winter wheat yields following organic and mineral fertilization was noted at both experimental fields (Figure 1). The obtained results showed that mineral nitrogen as described by Černý et al. (2010) was the main inorganic fertilizer affecting the winter wheat yields at both sites. Benefits of organic fertilization

doi: 10.17221/534/2016-PSE

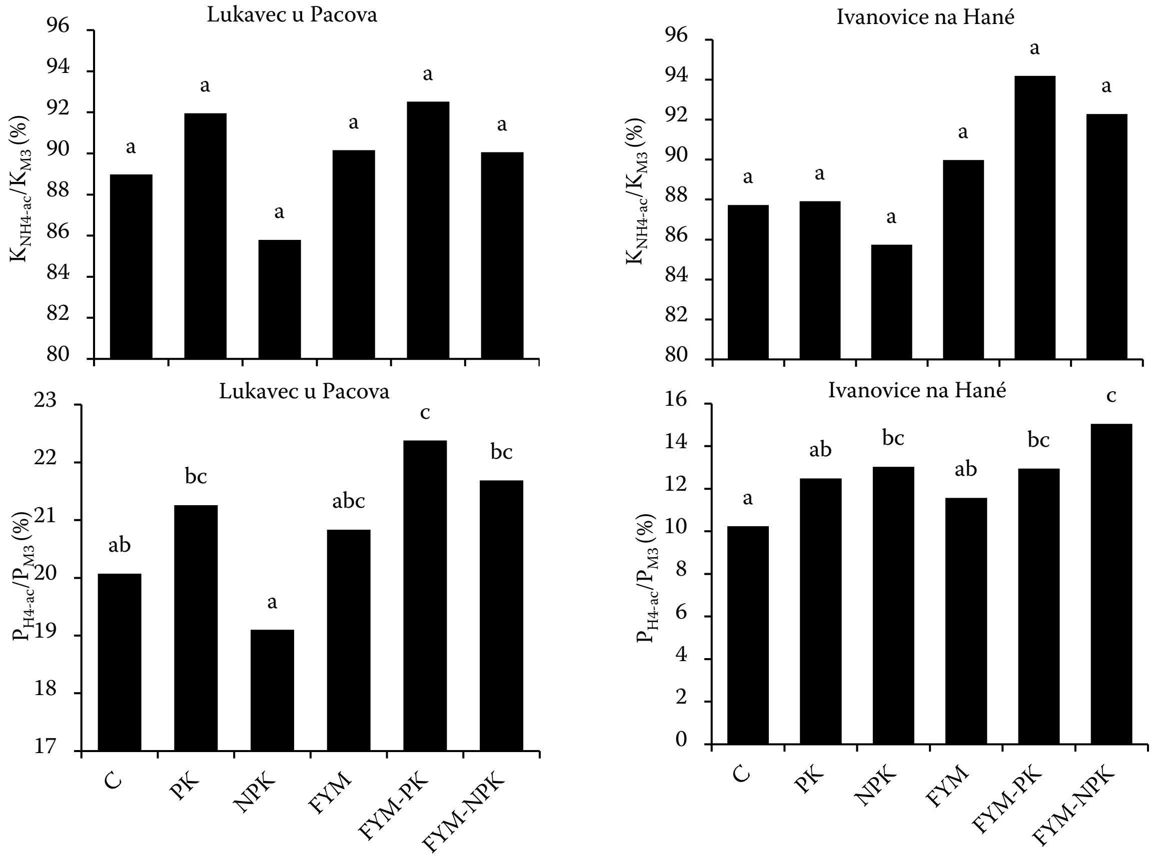

Figure 4. Average KNH_4-ac/K_{M3} and PNH_4-ac/P_{M3} ratio in soils (2010–2014). C – control; PK – mineral fertilization P and K; NPK – mineral fertilization NPK; FYM – farmyard manure; FYM-PK – farmyard manure + PK; FYM-NPK – farmyard manure + NPK. The same characters represent statistically identical values of the examined treatments

are evident in quantity and quality of wheat yields (Káš et al. 2010, Kismányoky and Dunai 2015). Our results are consistent with Jiang et al. (2006) who showed, in a 20-year field experiment, that the highest winter wheat yields were obtained following combined treatments with mineral fertilizers and FYM.

Table 3. Soil pH in the field experiment

Treatment	Lukavec u Pacova		Ivanovice na Hané	
	pH_{H2O}	pH_{KCl}	pH_{H2O}	pH_{KCl}
C	6.4^{ab}	5.6^{ab}	7.2^{b}	6.9^{b}
PK	6.4^{ab}	5.8^{ab}	7.1^{ab}	6.7^{ab}
NPK	6.1^{a}	5.4^{a}	6.8^{a}	6.4^{a}
FYM	6.4^{ab}	5.8^{ab}	7.0^{ab}	6.6^{ab}
FYM-PK	6.5^{b}	5.9^{b}	7.0^{ab}	6.6^{ab}
FYM-NPK	6.2^{a}	5.5^{a}	6.8^{a}	6.4^{a}

C – control; PK – mineral fertilization P and K; NPK – mineral fertilization NPK; FYM – farmyard manure; FYM-PK – farmyard manure + PK; FYM-NPK – farmyard manure + NPK. The same characters represent statistically identical values of the examined treatments

Mineral N fertilization caused a significant increase of overall P and K uptake in experimental plots by winter wheat (Table 2). The uptake of P and K by winter wheat treated with mineral NPK fertilizers exceeded the supply of P and K from this fertilization in degraded chernozem at Ivanovice (Table 2). This led to a negative balance of potassium and phosphorus in the plant-soil system under mineral nitrogen fertilization at Ivanovice. As a result, higher winter wheat uptake affected available and potentially available nutrient contents in the soils. However, no statistically significant correlation between K and P uptake by crops and their contents in soils was observed at any site. Our findings are consistent with Vanden Nest et al. (2014) and Zörb et al. (2014).

The fertilization system affected nutrient availability in soils. The fertilization with P and K and

doi: 10.17221/534/2016-PSE

combination of P and K with FYM increased the contents of nutrients according to both methods: Mehlich 3 and NH_4-acetate method. The K contents in the Ivanovice soils were significantly higher after FYM treatments compared with mineral fertilizers only and with control soils. A different situation was noted in the less fertile soils from Lukavec where the K concentrations differed significantly only for FYM-PK treatments. Liu et al. (2010) in a 30-year field experiment found a rapid decrease of K without straw or manure additions. In our experiments significantly lower soil K and P contents were found using NPK and FYM-NPK treatments compared with relevant PK treatments without N fertilization.

The ratio between exchangeable and total bioavailable nutrients – $K_{NH4\text{-}ac}/K_{M3}$ and $P_{NH4\text{-}ac}/P_{M3}$ varied for K between 85–94% at both sites and for P the ratio was in the soils from Ivanovice between 11–15% and 19–24% in the soils from Lukavec. The soil treatments with mineral N fertilizers caused a decrease of K and P contents in soils not only in the measured concentrations but also in relative values given by this ratio.

Despite the fact that no significant difference among treatments was found, a decreasing trend of $K_{NH4\text{-}ac}/K_{M3}$ in soils receiving mineral nitrogen was evident. Blake et al. (1999) showed that recoveries of K from farmyard manure (FYM) varied from 22–117% (values of > 100% indicating subsoil uptake or the release of reserves). Cong et al. (2016) showed that deficiencies of N, P and Mg decreased the effectiveness of applied K and may have caused increased leaching of K from the plough layer. Our results are consistent with these findings as an increase of the $Mg_{NH4\text{-}ac}/Mg_{M3}$ ratio after FYM-NPK treatments was also observed (data not shown). This increase could affect K concentrations in soils due to antagonism that could occur between K and Mg (Cong et al. 2016).

The interaction between N and P is the single most important nutrient interaction. It affects adsorption and desorption phosphorus capacities in the soils (Bhattacharyya et al. 2015). The lower ratio of $P_{NH4\text{-}ac}/P_{M3}$ in the control soils and also in the soils from Lukavec receiving mineral N indicates the decrease of readily available phosphorus fractions in comparison to total bioavailable P fractions (Mehlich 3 method). This could be possibly due to P uptake by crops. An increase of buffering capacity of soils with lower phosphorus content (for instance control soils) as showed in Kulhánek et al. (2008) can be the possible consequence of eventual new P additions to soils. The ratio $P_{NH4\text{-}ac}/P_{M3}$ found in the soils from Ivanovice showed an opposite trend and an increase of this ratio was noted. The soil pH in the Ivanovice control soils was 7.2 (pH_{H_2O}) and 6.9 (pH_{KCl}). The PK treatments decreased the soil pH to 7 (pH_{H_2O}) and 6.6 (pH_{KCl}) whereas the NPK treatments to 6.8 (pH_{H_2O}) and 6.4 (pH_{KCl}) (Table 3). Most mineral P in calcareous soils is present in various Ca-bound forms and there are great differences in P availability (Bhattacharyya et al. 2015). At Ivanovice, as showed by the ratio $P_{NH4\text{-}ac}/P_{M3}$, the relative phosphorus availability in the soils treated with mineral N-fertilizers and in combination with FYM increased corresponding with a slightly decreased pH. This is possibly due to the P desorption which could occur as a result of an interaction between organic molecule-P complexes with FYM (Bhattacharyya et al. 2015) on one side and pH changes on the other side.

In conclusion, the long-term fertilization with mineral and organic fertilizers affected the yields and overall export of nutrients from the field. This combination with mineral N fertilization can lead to a decrease of nutrient reserve in the soils. The readily available P and K fractions extracted by NH_4-acetate decreased under mineral N treatments more than total bioavailable fractions extracted by Mehlich 3. The N fertilization of alkaline soils can cause a pH decrease, which leads to a release of P reserve. More pronounced effects of long-term fertilization on nutrient contents were observed in the less fertile sandy-loam soils of Lukavec.

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Received on August 18, 2016
Accepted on November 3, 2016

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