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ORIGINAL PAPER

TRENDS IN PHOSPHORUS CONCENTRATIONS IN POTATO ORGANS DURING THE GROWING SEASON*

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Abstract

The assumption of this study was that the trends in phosphorus (P) concentrations in potato organs during the growing season can be used as indicators of the P supply to plants, and therefore they can be used as a tool to predict tuber yield. This hypothesis was validated based on the data from field experiments (2006-2008), with series of nutrients sequentially added (Absolute control – AC, NP, NPK, NPKS, and NPKSMg) to potatoes. The P concentration (P_c) was measured in potato vines, stolon + roots, and three fractions of potato tubers. The plants were periodically harvested in 10-day intervals, starting from BBCH 33 until maturity. The tuber yield, averaged over fertilization treatments, was 33.4, 53.7, and 41.6 t ha^{-1} in 2006, 2007, and 2008, respectively. Trends of P_c, regardless of potato part, significantly depended on weather conditions in particular seasons. The fertilizer P applied together with nitrogen resulted in the P_c increase in potato parts, but without a significant impact on the yield of tubers. Trends in P_c developed for vines and stolons + roots fairly well reflect the disturbance of the P supply to potato. No trend in P_c emerged in 2007, a year with an ample supply of water. This finding clearly informs us that P was not a factor limiting potato growth. The P_c trends in small-size potato tubers showed that the later the date of the optimum DAP for the P_{cmax} was, the higher yield of tubers was harvested. The quadratic regression models obtained for the small-, and medium-size tubers clearly demonstrate P shortage to these tuber fractions, following the DAP optimum. The same model, but for the large-size tubers, indicates the P dilution effect, which resulted from the excessive growth of tubers with respect to the amount of accumulated P. In consequence, the P_c in tubers was relatively low.

Keywords: growing season, vines, stolon + roots, tuber fractions, trends of phosphorus concentration.

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INTRODUCTION

The farmer's success in potato production depends on the tuber yield. According to Westerman and Kleinkopf (1985), the yield potential of potato is fully exploited provided the canopy remains active until tuber maturity. Any dysfunction in the supply of water or nutrient to plants during the growing season results in yield depression. Hence, an adequate supply of water and respective nutrients is crucial for potato plants' growth and tuber yield (Fixen, Bruulsema 2014). It is well documented that potato plants sufficiently supplied with phosphorus (P) increase the dry matter content and accumulation of other nutrients in tubers (Fernandes et al. 2015).

The quantity of P required by potato for high yield is in fact moderate, but its recommended doses in farming practice are high (Westermann 2005). There are numerous reasons for recommending elevated P doses. The main one is the element's low recovery from the applied fertilizer, seldom exceeding 10% (White et al. 2018). Another reason is the extremely high sensitiveness of potato to the supply of P at the onset of stolon swelling (tuberization) and at the tuber extension (Allisson et al. 2001). The inherent weakness of potato plant in nutrient absorption is due to its shallow roots system, spreading mainly in the topsoil (Kolbe, Stephan-Beckman 1997*b*). As reported by Lahlou et al. (2003), the fresh tuber yield can be predicted just based on the root mass. These authors also showed that drought affects negatively both the mass of roots and length of stolons. It is well documented that any reduction in the root size results in the lower uptake of nutrients, particularly the ones which move slowly in the soil body, like potassium and phosphorus (Bhadoria et al. 1991). The main attribute of inorganic phosphorus ions (Pi) present in the soil solution is their low coefficient of diffusion. Under conditions of the limited water content, the transfer of P_i toward the plant root is therefore considerably inhibited (Fixen, Bruulsema 2014). Consequently, potato plants are strongly sensitive to drought, whenever it occurs during the growing season.

As shown in the extensive review by Kolbe and Stephan-Beckman (1997*a*,*b*), the rate of potato growth and the development of its yield components are highly sensitive to nutrient supply. The main source of P to the growing tuber is its resources accumulated in aerial parts. Therefore, the amount of P in this plant part is crucial for the rate of tuber expansion. However, as reported by White et al (2018), phosphorus accumulates in tubers up to the full maturity. It can be hypothesized that other potatoes parts, including underground organs such as stolons + roots participate in P supply to the growing tuber.

The prediction of tuber yield, in general, is based on the evaluation of P concentration (Pc) in the aerial plant parts such as i) young and fully developed leaves, ii) all leaves, iii) leaf petioles, iv) stems (Walworth, Muniz 1993). As a rule, the diagnosis of potato plant nutritional status is conducted in its early stages of growth (Grzebisz et al. 2018). Other potato parts are not considered as possessing the yield diagnostic worth. The potato tuber is evaluated only for its nutritive value as an important staple food for humans (White et al. 2018).

The main objective of this study was to determine trends in P concentrations during the growing season in vines, stolons + roots, and three tuber fractions: small, medium, and large. These trends were evaluated under natural, rain-fed conditions, modified by the gradually increased set of applied nutrients. Another objective was the in-season evaluation of the usefulness of potato parts for the yield prediction.

MATERIALS AND METHODS

Experimental site

The study is based on data obtained from field trials with potato (*Solanum tuberosum* L.), which were carried out in 2006-2008 at the Brody Experimental Farm (Poznan University of Life Sciences, 52°44′ N; 16°28′ E). The field experiment was established on soil originated from loamy sand, underlain by sandy loam and classified as Albic Luvisol. The content of available nutrients, measured each year before the fertilizer's application to the topsoil, was in the high/very high class for phosphorus (80-95 mg P kg^{-1} soil), medium for potassium (130-150 mg K kg^{-1} soil) (double lactate method), medium for magnesium (58-62 mg Mg kg^{-1} soil) (Schachtschabel method). The amount of mineral N (N_{min}) was in the range 23-30 kg ha^{-1} (0.01 mol dm^{-3} $CaCl_2$). The soil pH was 5.6-6.0 (1 mol dm^{-3} KCl). The meteorological data prove that precipitations were highly variable, especially in June, a month critical for potato tuberization. Water deficits appeared in June and July 2006, and in July 2008 (Table 1).

Table 1

Characteristics of meteorological conditions during the study, precipitation [mm]

Months	Temperature (°C)				Precipitation (mm)			
	2006	2007	2008	1961-2009	2006	2007	2008	1961-2009
March	0.5	6.5	4.2	2.9	25.4	71.9	76.0	40.1
April	8.7	10.5	8.7	7.9	47.2	4.8	121.0	38.1
May	13.7	14.5	15.2	13.2	41.4	150.0	20.0	56.7
June	19.9	19.2	19.1	16.4	7.7	55.6	8.6	62.7
July	24.2	18.6	20.0	18.1	9.9	96.2	80.0	77.2
August	17.4	18.1	18.6	17.5	189.0	71.0	172.0	66.7
September	16.3	13.2	18.8	13.3	24.5	49.0	30.0	48.8

Experimental design

Data for this study originated from a field trial consisting of five treatments, differing in the composition of sequentially added sets of nutrients, on plots arranged in a completely randomized block design, and replicated four times. The fertilized treatments were as follows: i) absolute control (AC, no fertilizers added), ii) NP, ii) NPK-MOP (K applied as muriate of potash), NPKS-SOP (K applied as potassium sulfate), NPKSMg (Patentkali). Phosphorus in the dose of 38.7 kg P ha^{-1} was applied as di-ammonium phosphate. Potassium was applied at the dose of 166 kg K ha^{-1}. Both nutrients were applied two weeks before potato planting. The dose of S applied with SOP and Patentkali was 69.1 and 110.7 kg ha^{-1}, respectively. The dose of Mg was 39.1 kg ha^{-1}. Nitrogen used in the form of ammonium nitrate (34% N) was divided into two sub-doses and applied to potato before planting: 70 kg ha^{-1}, and in BBCH 20: 60 kg ha^{-1}. The total area of a single plot was 58.5 m^2. The *Corona* variety of potato was planted in the second half of April and harvested from an area of 19.5 m^2 at the end of September.

Soil and plant material and analyses

Concentrations of soil available forms of P and K were determined following the Egner-Riehm method (PN-R-04023:1996 and PN-R-04022:1996+Az12002); Mg was determined according to Schachtschabel (PN-R- 04020:1994+Az:2004), and the soil pH was measured potentiometrically (ISO 10390:1997). Plant material used for dry matter determination and measurement of nutrient concentrations was collected from an area of 1.0 m^2. Each year, plant material was sampled during the growing season in consecutive days after planting (DAP): 57, 68, 78, 89, 99, 110, 121, 131, 141, 152. The sampled material was then divided, depending on the potato stage of growth, into subsamples of vines, stolon + roots. Tubers were divided into three fractions: small (< 3 cm), medium (3.5-5 cm), and large (> 5 cm). For phosphorus, the harvested plant sample was dried at 65°C and then mineralized at 600°C. The ash was dissolved in 33% HNO_3. The P concentration was measured by the vanadium-molybdenum method using a Specord 2XX/40 (Analytik Jena, Jena, Germany) at a wavelength of 436 nm. Results are expressed on a dry matter basis.

Statistical analyses

The collected data were subjected to a conventional analysis of variance using Statistica® 10 (StatSoft, Krakow, Poland). Differences between the treatments were evaluated with the Tukey's test. In tables, figures and developed equations, the results from the *F* test (***, **, *) indicate significance at the P < 0.001, 0.01, and 0.05, respectively. In the second step of the diagnostic procedure, i.e. stepwise regression, was applied to define an optimal set of variables for a given crop characteristic. In the computational procedure, a consecutive variable was removed from the multiple linear regressions in a step-by-step manner. The best regression model was chosen based on the highest F-value for the model and significance of all independent variables.

RESULTS AND DISCUSSION

Vines

The trends in phosphorus concentrations (P_c) in potato vines during the growing seasons were significantly driven by the weather in consecutive years, as shown for the NPK treatment (Figure 1). In 2006, the P_c pattern

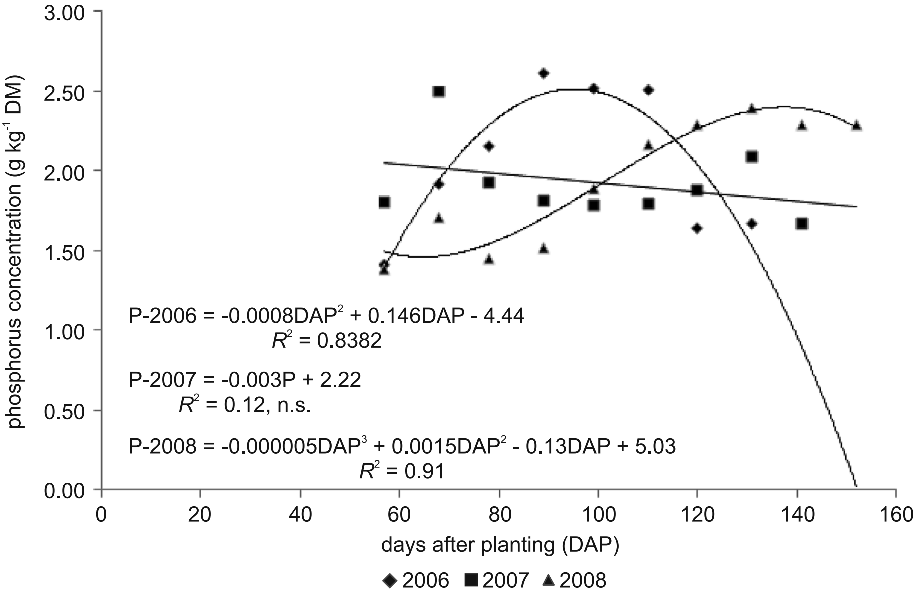

Fig. 1. Trends of phosphorus concentration in potato vines during the growing season

followed the quadratic regression model, achieving the maximum P_c of 2.2 g kg^{-1} DM in the 92nd DAP. In 2007, the recorded linear trend was not significant, indicating however the maximum P_c on 68 DAP. Then, the P concentration slowly decreased along the growing season. The significant increase of P_c in potato tops during the period from 57 to 68 DAP clearly indicates that its uptake preceded the rate of dry matter production by potato crop. This phenomenon was probably due to the vigorous growth of roots (White et al. 2018). This pattern of P_c in potato vines was a prerequisite of a very high yield of tubers. In 2008, the pattern of P_c was even more complicated. It followed the 3rd degree regression model with the inflation point on 100 DAP. The P_c increased from this point onward, reaching the maximum around 140 DAP. It can be concluded that the patterns which revealed in 2006 and 2008, i.e. in years with water shortage, indicate some disturbance in the P accumulation in the aerial potatio part.

The effect of the applied fertilizers on $P_{c,}$ despite year-to-year variability, was almost regular (Table 2). In all years, the effect of the NP treatment on P_c was significant with respect to the absolute control. The highest diffe-

Table 2

Phosphorus concentration in potato vines in consecutive years (g kg^{-1} DM)

Treatments	Days after planting (DAP)									
	57	68	78	89	99	110	120	131	141	152
2006										
AC	1.1^{a}	1.6^{a}	1.9^{a}	2.0^{a}	2.1^{a}	1.9^{a}	1.6^{a}	1.0^{a}	-	-
NP	1.4^{b}	1.8^{b}	2.3^{b}	2.4^{c}	2.6^{b}	2.5^{b}	1.7^{b}	1.6^{c}	-	-
NPK	1.4^{b}	1.9^{b}	2.2^{b}	2.6^{c}	2.5^{b}	2.5^{b}	1.7^{b}	1.7^{c}	-	-
NPKS	1.5^{b}	1.9^{b}	2.1^{a}	2.2^{b}	2.2^{b}	2.5^{b}	1.6^{a}	1.7^{c}	-	-
NPKSMg	1.4^{b}	21^{b}	2.1^{a}	2.2^{b}	2.4^{b}	2.6^{b}	1.7^{b}	1.2^{b}	-	-
F value	9.4^{***}	10.3^{***}	18.5^{***}	39.2^{***}	26.6^{***}	22.1^{***}	7.2^{**}	117.9^{***}	-	-
2007										
AC	1.5^{a}	2.1^{a}	1.8^{a}	1.8^{a}	1.8^{a}	1.7^{a}	1.7^{a}	1.8^{a}	1.5^{a}	-
NP	1.9^{b}	2.2^{ab}	1.9^{ab}	1.8^{a}	1.8^{a}	1.8^{a}	2.0^{b}	2.1^{a}	1.7^{b}	-
NPK	1.8^{b}	2.5^{d}	1.9^{ab}	1.8^{a}	1.8^{a}	1.8^{a}	1.9^{ab}	2.1^{a}	1.7^{b}	-
NPKS	1.9^{b}	2.3^{bc}	2.0^{b}	2.0^{b}	2.0^{b}	2.0^{b}	1.9^{ab}	2.1^{a}	1.7^{b}	-
NPKSMg	1.9^{b}	2.5^{cd}	2.0^{b}	2.0^{b}	2.0^{b}	2.1^{b}	2.0^{b}	2.5^{b}	2.0^{c}	-
F value	15.4^{***}	22.9^{***}	6.1^{**}	21.0^{***}	35.3^{***}	12.1^{***}	14.3^{***}	13.9^{***}	14.0^{***}	-
2008										
AC	1.4	1.5^{a}	1.2^{a}	1.5^{a}	1.7^{a}	2.1	2.1^{a}	2.2^{a}	2.2^{a}	1.8^{a}
NP	1.4	1.7^{ab}	1.4^{b}	1.7^{a}	2.0^{b}	2.3	2.4^{b}	2.5^{ab}	2.3^{a}	2.4^{b}
NPK	1.4	1.7^{b}	1.5^{b}	1.5^{a}	1.9^{ab}	2.2	2.3^{ab}	2.4^{ab}	2.4^{a}	2.3^{b}
NPKS	1.5	1.9^{c}	1.3^{ab}	1.7^{a}	2.0^{ab}	2.1	2.3^{ab}	2.4^{ab}	2.2^{a}	2.3^{b}
NPKSMg	1.4	1.7^{b}	1.3^{ab}	1.7^{a}	2.0^{ab}	2.3	2.3^{ab}	2.7^{b}	2.3^{a}	2.4^{b}
F value	1.1	17.3^{***}	5.2^{**}	3.4^{*}	3.6^{*}	1.3	3.8^{*}	8.2^{**}	4.8^{*}	8.2^{**}

***. **. * significant at $p < 0.001$; < 0.01; <0.05, respectively; n.s. – not significant;
^{a} the same letter indicates a lack of significant differences within the treatment.

rences between these two treatments were recorded in the very dry 2006. This type of response to P fertilizer is typical for potato plants grown under condition of P shortage in soil (GREWAL, TREHAN 1993). In contrast, the smallest difference was found in the dry 2008. It is important to stress that the effect arising from the interaction with other nutrients on P_c was not consistent. In 2006, it was recorded on the NPK plot on 89 DAP. In 2007, a significantly higher P_c was also recorded for the NPK treatment, but on 68 DAP.

In 2008, the impact of other nutrients on P_c was not observed. As reported by Westermann and Kleinkopf (1985), the P_c below 2.2 g kg^{-1} DM in the tops indicates disturbance in the tuber growth. In our study, this hypothesis was corroborated for early stages of potato growth, as recorded in 2006 and especially in 2008. In 2007, the P_c was above this threshold at the stolon swelling period (57 → 68 DAP), subsequently resulting in the highest yield of fresh tubers. In the later stages of potato growth, P_c was below 2.2 g kg^{-1} DM, especially during the period of intensive tuber expansion.

The applied stepwise regression test showed that the yield prediction based on P_c in potato vines requires data from two distinct harvests, i.e. 68 and 120 DAP. The regression equation obtained is as follows:

$$Y = -89.3 + 398P_{c\text{-}DAP89} + 276P_{c\text{-}DAP120} \text{ for } R^2 = 0.88 \text{ and } n = 15 \quad (1)$$

This equation demonstrates that the yield of fresh tuber significantly depended on P supply to potato in the period extending from the stolon swelling (68 DAP) up to the full stage of tuber bulking (120 DAP). The importance of P supply to potato plants in the first critical period is well documented and is frequently used for diagnosis of this crop's nutritional status (Grzebisz et al. 2018). The second harvesting date included into this model indicates that the high P_c in the vines is required by the crop during the intensive ingrowth of the tubers. This study clearly documented that the critical period of P_c in the vines is much wider than this proposed Zamuner et al. (2016). This study showed that this period extends from the stage of stolon swelling up to the stage of the full tuber bulking.

Stolons + roots

The pattern of P_c in the stolons + roots was significantly governed by the weather in a particular year. As shown for the NPK treatment, the P_c trends during the growing season followed the quadratic regression model in years with water stress (2006 and 2008) – Figure 2. A linear but not significant model was recorded in 2007, a year with an ample water supply to potato during summer. This trend is in agreement with a study by White et al. (2005), who showed that P_c in this potato parts reflects its supply from soil resources. In 2006 and 2008, the lowest P_c was recorded on 97 and 118 DAP, respectively. The P_c decrease was due to severe drought, which took place in June and July in 2006, and in May and June in 2008. The availability of P to plants under stress undergoes drastic reduction both due to the reduction in the root system and a decrease of the coefficient of diffusion for P ions. As a result, the P_c decreases in a given plant part (Lahlou et al. 2003, Fixen, Bruulsema 2014). Consequently, the P_c in the stolon + roots was much lower due to the insufficient P uptake and its subsequent redistribution between other potato parts. In 2007, P_c was constant during the entire period of potato growth, achieving on average 1.2 g kg^{-1} DM. This value, as indicated by the highest yield of potato in 2007, was sufficient to keep the fast growth of potato plants.

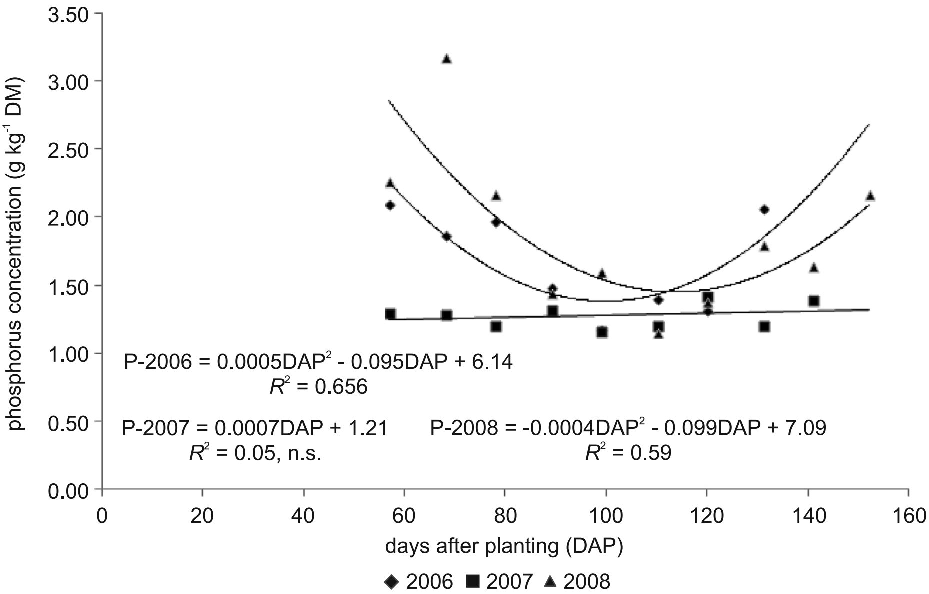

Fig. 2. Trends of phosphorus concentration in potato stolons + roots during the growing season

The effect of phosphorus fertilization on P_c in the stolon + root was observable in all years of study (Table 3). The highest differences between P_c in plants grown in the absolute control variant and those fertilized with NP were recorded in 2006 and 2008, i.e. years with water shortage. The most pronounced differences were recorded in the early stages of potato growth. In general, the effect of potassium and other nutrients on P_c was non-consistent, manifesting iteself sporadically. The P_c in stolon + root due to its high in-season variability did not show any predictive worth for the tuber yield.

Small-size tuber

The pattern of P_c concentrations in the small-size tubers followed the quadratic regression model. It was year-to-year variable, same as identified for the previously presented organs (Figure 3). In 2006, the average P_c was the highest, achieving the maximum (P_{cmax}) of 4.9 g kg^{-1} DM on 107 DAP. At potato maturity, it dropped down to around 3.0 g kg^{-1} DM. In 2007, the P_{cmax} was significantly lower, achieving of 3.57 g kg^{-1} DM on 138 DAP. At potato maturity, P_c was only slightly lower, amounting to 3.4 kg^{-1} DM. In 2008, the P_{cmax} of 3.2 g kg^{-1} DM was reached on 113 DAP, i.e. 25 days earlier as compared to 2007. The stabile course of P_c trend, as recorded in 2007, can be considered as an indicator of a good supply of phosphorus to the growing tubers. It can be concluded that a stable P supply to young tubers is a prerequisite of high yield of fresh tubers.

Table 3

Phosphorus concentration in potato stolon + roots in consecutive years (g kg^{-1} DM)

Treatments	Days after planting (DAP)									
	57	68	78	89	99	110	120	131	141	152
2006										
AC	1.8^{a}	1.4^{a}	1.4	1.2^{a}	1.1^{a}	1.2^{a}	1.2	1.3^{a}	-	-
NP	2.4^{b}	2.0^{b}	1.6	1.4^{ab}	1.2^{a}	1.3^{ab}	1.3	1.9^{ab}	-	-
NPK	2.1^{ab}	1.9^{b}	1.8	1.5^{ab}	1.2^{a}	1.4^{ab}	1.3	2.1^{b}	-	-
NPKS	2.5^{b}	2.2^{b}	2.1	2.0^{ab}	1.8^{b}	1.6^{b}	1.5	2.2^{b}	-	-
NPKSMg	2.0^{a}	2.0^{b}	2.0	2.0^{b}	1.9^{b}	1.6^{b}	1.5	1.6^{ab}	-	-
F value	5.3^{**}	7.7^{**}	2.3	6.6^{**}	89.9^{***}	5.4^{**}	1.0	4.4^{*}	-	-
2007										
AC	1.1^{a}	1.2^{a}	1.0^{a}	1.2^{a}	1.1^{a}	1.2^{a}	1.1^{a}	1.1	1.2^{a}	-
NP	1.2^{b}	1.3^{ab}	1.2^{b}	1.4^{b}	1.2^{ab}	1.2^{a}	1.4^{b}	1.2	1.5^{ab}	-
NPK	1.3^{c}	1.3^{ab}	1.2^{b}	1.3^{b}	1.2^{ab}	1.2^{a}	1.4^{b}	1.2	1.4^{a}	-
NPKS	1.3^{c}	1.3^{b}	1.2^{b}	1.3^{b}	1.1^{a}	1.6^{b}	1.3^{ab}	1.3	1.4^{a}	-
NPKSMg	1.3^{c}	1.3^{b}	1.1^{ab}	1.3^{b}	1.2^{b}	1.6^{b}	1.3^{ab}	1.4	1.7^{b}	-
F value	42.3^{***}	5.4^{**}	4.4^{*}	5.1^{***}	6.0^{**}	121^{***}	4.2^{*}	1.8	$.9^{**}$	-
2008										
AC	1.8^{a}	2.3^{a}	2.0^{a}	2.0	1.4^{a}	1.1	1.1^{a}	1.0	1.6^{a}	1.9^{a}
NP	2.3^{ab}	3.1^{b}	2.3^{b}	2.2	1.6^{b}	1.2	1.4^{b}	1.1	1.9^{b}	2.3^{ab}
NPK	2.3^{ab}	3.2^{b}	2.2^{b}	2.1	1.4^{a}	1.2	1.4^{b}	1.1	1.8^{ab}	2.2^{ab}
NPKS	2.3^{ab}	3.1^{b}	2.5^{b}	2.0	1.6^{b}	1.1	1.3^{ab}	1.0	1.9^{b}	2.2^{ab}
NPKSMg	2.5^{b}	3.1^{b}	2.2^{b}	2.1	1.6^{b}	1.1	1.3^{ab}	1.0	1.9^{b}	2.2^{ab}
F value	4.8^{*}	8.2^{**}	16.2^{***}	1.3	3.4^{*}	0.9	5.2^{**}	0.2	3.6^{*}	9.9^{***}

***. **. * significant at $p < 0.001$; < 0.01; <0.05, respectively; n.s. – not significant;
^{a} the same letter indicates a lack of significant differences within the treatment.

The effect of P fertilizer on P_c in small-size tubers was irregular in a particular growing season (Table 4). In 2006, it became significant after 99 DAP. The highest difference between the absolute control and NP plot was recorded on 110 DAP. In 2007, the biggest difference between these two treatments emerged in the early stages of potato growth. A constant P_c gap between both treatments was recorded in 2008, a year with drought at the beginning of the growing season. This year is a classic example of the importance of the current P fertilization to potato. The effect of the other nutrients, i.e. K, S, and Mg on P_c concentration was highly variable. As a rule, it was the most pronounced in 2007, a year with the highest yield of tuber. The positive impact of these nutrients was revealed since 99 DAP and lasted until 120 DAP. This is the period of the most rapid tuber enlragement, and

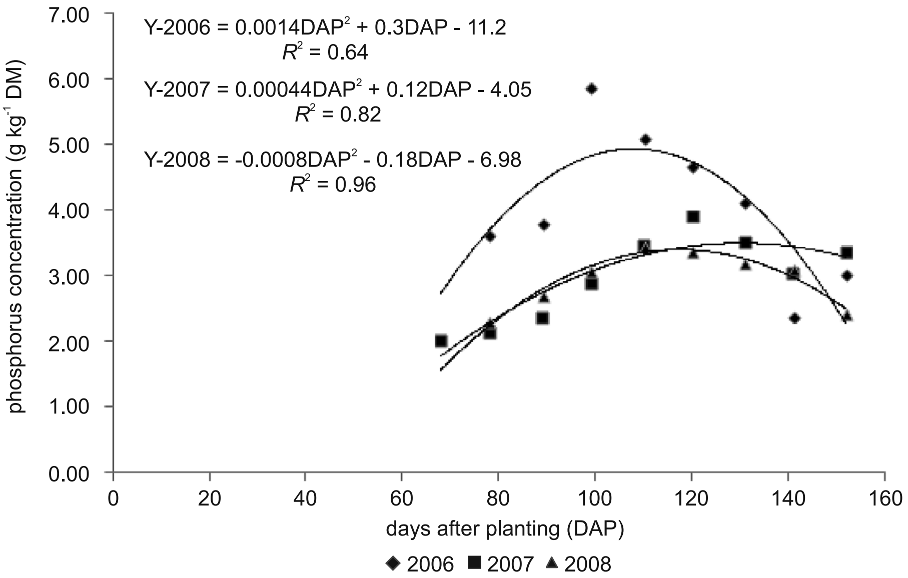

Fig. 3. Trends of phosphorus concentration in the small-size tubers during the growing season

significantly depends on the supply of P to the growing tubers (Kolbe, Stephan-Beckmann 1997*b*, White et al. 2018).

The fresh yield of tuber showed the highest sensitivity to P_c in the small-size tubers on two distinct sampling dates, i.e. on 78 and on 141 DAP. On the first harvesting date, the year-to-year variability in P_c was the key factor:

2006: $Y = 33P_c + 39.7$ for R^2 0.05; n.s.

2007: $Y = 346.1P_c – 18.1$ for $R^2 = 0.70$;

2008: $Y = -22900P_c^2 + 15350P_c – 2524$ for $R^2 = 0.85$.

The linear model as developed for 2007 clearly indicates the importance of P supply to the high-yielding potato crop. The key reason of high P demand was the elevated biomass of growing tubers, resulting in P_c dilution. In contrast, in 2008, the maximum tuber yield of 48 t ha^{-1} was predicted by P_c = 3.35 g kg^{-1} DM. On 141 DAP, the impact of P_c on the tuber yield was significant, irrespectively of the weather pattern in a particular year:

2006: $Y = -28085P_c^2 + 13295P_c + 1542$ for $R^2 = 0.88$;

2007: $Y = 660.7P_c –144.7$ for $R^2 = 0.60$;

2008: $Y = 203.4P_c – 18.1$ for $R^2 = 0.82$.

In 2006, the maximum P_c of 2.4 g kg^{-1} DM resulted in the yield of 31.5 t ha^{-1} tubers. It was found that in the other two years, the tuber yield increased linearly with P_c in the small-size tubers. This trend corroborates the opinion expressed by White et al. (2018), who stressed a high requirement of potato tuber for P, which lasted to the end of the growing season.

Table 4

Phosphorus concentration in the small-size tubers in consecutive years (g kg^{-1} DM)

Treatments	Days after planting (DAP)								
	68	78	89	99	110	120	131	141	152
				2006					
AC	-	3.5	3.5	5.3^{a}	4.6^{a}	4.2	3.9^{ab}	2.2^{a}	2.4^{a}
NP	-	3.5	3.3	5.8^{b}	5.4^{bc}	4.5	4.0^{ab}	2.5^{b}	2.9^{b}
NPK	-	3.6	3.8	5.9^{b}	5.1^{b}	4.7	4.1^{b}	2.4^{ab}	3.0^{b}
NPKS	-	3.6	3.7	5.8^{b}	5.5^{c}	4.7	3.7^{a}	2.5^{b}	3.1^{b}
NPKSMg	-	3.4	3.3	5.9^{b}	5.1^{ab}	4.6	3.8^{ab}	2.4^{a}	3.0^{b}
F value	-	3	1.7	35.7^{***}	20.1^{***}	1.1	2.9^{*}	3.6^{*}	11.3^{***}
				2007					
AC	1.7^{a}	1.6^{a}	1.9^{a}	2.2^{a}	2.8^{a}	3.1^{a}	3.5^{a}	2.8	2.8^{a}
NP	2.3^{c}	2.1^{b}	2.4^{b}	2.6^{ab}	2.8^{a}	3.6^{b}	3.7^{a}	3.0	2.9^{a}
NPK	2.0^{abc}	2.2^{b}	2.4^{b}	2.9^{b}	3.5^{b}	3.9^{b}	3.5^{a}	3.1	3.4^{b}
NPKS	2.1^{bc}	2.2^{b}	2.4^{b}	2.9^{b}	3.5^{b}	3.9^{b}	3.6^{a}	3.1	3.2^{b}
NPKSMg	2.0^{ab}	2.3^{b}	2.5^{b}	2.9^{b}	3.8^{b}	3.8^{b}	3.5^{a}	3.1	3.4^{b}
F value	42.3^{***}	5.4^{**}	4.4^{*}	25.1^{***}	6.0^{**}	121^{***}	4.2^{*}	1.8	6.9^{**}
				2008					
AC	-	2.1	2.0^{a}	2.2^{a}	2.2^{a}	2.2^{a}	2.3^{a}	2.2^{a}	2.0^{a}
NP	-	2.6	2.8^{b}	2.6^{b}	3.5^{c}	3.2^{b}	3.2^{b}	3.1^{b}	2.6^{b}
NPK	-	2.3	2.7^{b}	2.5^{b}	3.5^{c}	3.4^{b}	3.2^{b}	3.1^{b}	2.4^{b}
NPKS	-	2.3	2.7^{b}	2.4^{a}	3.5^{c}	3.2^{b}	3.3^{b}	3.2^{b}	2.3^{b}
NPKSMg	-	2.2	2.7^{b}	2.4^{b}	2.9^{b}	3.3^{b}	3.2^{b}	3.1^{b}	2.5^{b}
F value	-	2.7	21.7^{***}	5.5^{**}	60.6^{***}	30.0^{***}	19.0^{***}	30.8^{***}	10.6^{***}

***. **. * significant at $p < 0.001$; < 0.01; <0.05, respectively; n.s. – not significant;
^{a} the same letter indicates a lack of significant differences within the treatment.

Medium-size tubers

The trends in P_c for medium-size tubers showed a high year-to-year variability (Figure 4). In 2006, the P_c patterns followed the quadratic regression model. The P_{cmax} of 4.6 g kg^{-1} DM was revealed on 127 DAP. Then, it decreased drastically, down to 3.0 g kg^{-1} DM at harvest. The same pattern of P_c was observed in 2007. However, its course was much more gentle. The P_{cmax} of 3.8 kg^{-1} DM was recorded on 118 DAP. The P_c decrease following the P_{cmax} was also sharp, down to 3.0 g kg^{-1} DM at harvest. In 2008, P_c showed high and irregular variability during the growing season. The quadratic model of P_c, as recorded in 2006 and 2007, clearly indicated P dilution. It was revealed during the maturation phase of potato plants.

The effect of P fertilizer on P_c was evaluated with respect to the absolute

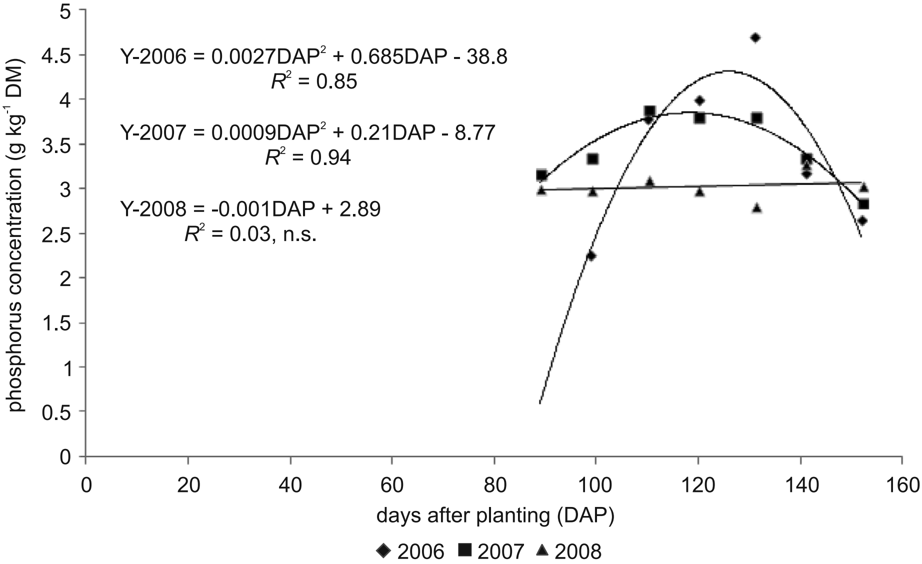

Fig. 4. Trends of phosphorus concentration in the medium-size tubers during the growing season

control (Table 5). The biggest difference between these two treatments was recorded, irrespectively of the year, in the beginning of the growth of this potato fraction. In 2006, the impact of P fertilizer disappeared extremely early, despite very high Pc values. In 2007, the effect of P fertilizer was consistent during the whole growing season. The difference between AC and NP treatments was the biggest during the autumn tuber bulking, i.e. it started on 110 DAP and continued onward. The observed P_c gap was much deeper compared to differences in the tuber yield, which was 44 t ha^{-1} for the NP treatment and 40 t ha^{-1} for the AC. The latter value indicates high dilution of P in the growing tubers, but this resulted from the ample supply of water. The same phenomenon was observed by Grzebisz et al. (2018) for P_c in seeds of oilseed rape. In 2008, an identical pattern of P fertilizer impact on its concentration in tubers was observed. However, yields were much lower. The effect of the other nutrients on P_c depended on both the year and potato growth stage. In 2006, significant impact of potassium fertilizer was revealed only on 141 DAP, but this treatment yielded the highest. The impact of S and S+Mg on the P_c was also recorded in later stages of the potato growth, but it did not result in a simultaneous yield increase. In 2007, the effect of the other nutrients on P_c persisted during the entire period of tuber extension, disappearing during the potato maturation phase. In 2008, the effect of the other nutrients on P_c was significant during the whole period of the tuber growth. The important impact of K and S+Mg, in 2007, and S in 2008 on P_c indicates the role of these nutrients in exploiting the yielding potential of potato.

Table 5

Phosphorus concentration in the medium-size tubers in consecutive years (g kg^{-1} DM)

Treatments	Days after planting (DAP)						
	89	99	110	120	131	141	152
2006							
AC	-	2.1^{a}	3.5^{a}	3.8^{a}	4.7^{a}	2.6^{a}	2.4
NP	-	2.9^{d}	3.6^{a}	3.9^{a}	4.7^{a}	3.0^{ab}	2.6
NPK	-	2.3^{ab}	3.8^{a}	4.0^{a}	4.7^{a}	3.2^{b}	2.7
NPKS	-	2.5^{bc}	3.9^{a}	4.1^{ab}	5.2^{ab}	3.5^{c}	2.6
NPKSMg	-	2.6^{cd}	3.5^{a}	4.5^{b}	5.4^{b}	3.6^{c}	2.7
F value	-	32.0***	3.3*	7.0**	6.5**	17.7***	0.7
2007							
AC	1.8^{a}	2.4^{a}	2.3^{a}	2.5^{a}	2.6^{a}	2.3^{a}	1.9^{a}
NP	2.6^{b}	2.7^{ab}	3.5^{b}	3.5^{b}	3.6^{b}	3.5^{b}	3.1^{b}
NPK	3.2^{c}	3.3^{abc}	3.9^{bc}	3.8^{b}	3.8^{bc}	3.3^{b}	2.8^{b}
NPKS	3.5^{c}	3.8^{bc}	4.1^{bc}	4.2^{b}	4.2^{c}	3.4^{b}	3.0^{b}
NPKSMg	3.4^{c}	4.1^{c}	4.5^{c}	4.4^{b}	4.2^{c}	3.6^{b}	2.9^{b}
F value	67.1***	5.5**	24.8***	17.3***	40.0***	16.7***	8.1**
2008							
AC	2.5^{a}	2.2^{a}	2.2^{a}	2.5^{a}	2.7^{a}	2.9^{a}	2.6^{a}
NP	3.0^{ab}	2.2^{a}	2.5^{b}	2.9^{ab}	3.0^{ab}	3.3^{ab}	2.7^{ab}
NPK	3.0^{ab}	3.0^{b}	3.1^{bc}	2.8^{ab}	3.0^{ab}	3.3^{ab}	3.0^{b}
NPKS	3.5^{b}	3.1^{b}	3.5^{c}	3.0^{b}	3.2^{b}	3.5^{b}	3.0^{b}
NPKSMg	2.9^{ab}	3.1^{b}	3.5^{c}	3.0^{b}	3.2^{b}	3.5^{b}	2.7^{ab}
F value	5.4**	39.3***	78.6***	4.6*	4.6*	4.6*	5.0**

***. **. * significant at $p < 0.001$; < 0.01; <0.05, respectively; n.s. – not significant;
^{a} the same letter indicates a lack of significant differences within the treatment.

The simple regression equation clearly indicates 99 DAP as the optimum stage of potato growth for its maximum yield (Y) prediction based on P_c in the medium-size tubers. The developed equation is as follows:

$$Y = 186.2P_c - 11.3 \text{ for } n = 15,\ R^2 = 0.71, \text{ and } P \leq 0.001.$$

This equation corroborates the hypothesis developed by White et al. (2018) that phosphorus accumulates in the potato tuber until the end of its growth. The dilution phenomenon in the medium-size tuber fraction was not proved. This finding indicates that this particular potato fraction did not suffered due to the limited P supply, irrespectively on the weather pattern in the consecutive years of study.

Large-size tubers

The patterns of P_c trends recorded for large-size tubers stress the importance of P supply to potato crop. As shown in Figure 5, irrespectively of the

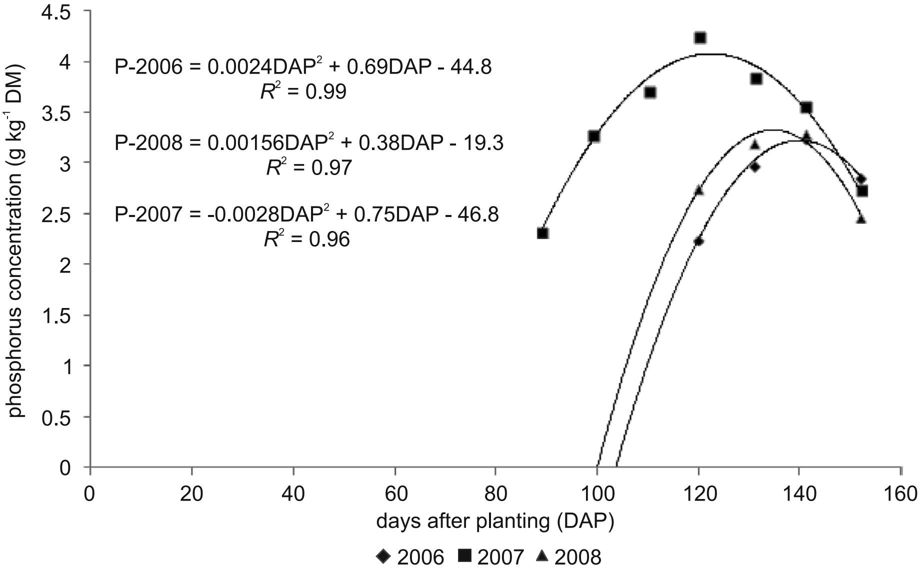

Fig. 5. Trends of phosphorus concentration in the large-size tubers during the growing season

growing season, P_c followed the quadrate regression model. Differences between the years, as an indirect measure of P supply to the enlarging tubers, were expressed by parameters of the developed equations. The highest yield was recorded in 2007. It was achieved in a year with an ample supply of water in critical months of stolon swelling and tuber bulking, i.e. from June to August. The highest yield recorded in 2007 was significantly connected with the duration of the growth of large tubers. In 2007, owing to favourable weather conditions, the first large tuber was harvested on 89 DAP, whereas in the other years large tubers were found on 120 DAP. In that particular year, the P_{cmax} of 4.1 g kg^{-1} DM was achieved on 122 DAP. In 2006, a year with water stress in June and July, the P_{cmax} of 3.1 g kg^{-1} DM was recorded on 142 DAP. In 2008, the P_{cmax} of 3.5 g kg^{-1} DM was found on 135 DAP. In both years with water stress, P_c was not only significantly lower but also occurred much later than in 2007.

The right evaluation of P_c requires data on the tuber yield. In this study, the final P_c in the large-size tubers ranged from 2.5 to 2.9 g kg^{-1} DM for 2008 and 2006, respectively. These values are in the ranges reported by KLIKOCKA et al. (2015). The P_c in tubers from the long-term experiment in the Czech Republic ranged from 1.5 to 2.2. g kg^{-1} DM (ŠREK et al. 2010), and the tuber yield ranged from 22 to 32 t ha^{-1}. In our study, such low P_c was detected only on the AC plot in 2008, a year with severe drought in May and June.

The tuber yield harvested on the AC plot was 28 t ha^{-1}. These two sets of data clearly indicate a good supply of P to the potato plant during the entire plant growing season, resulting in relatively high yields of tubers.

The effect of P fertilizer on P_c was first compared with its value for the NP and the absolute control and then also with treatments fertilized with K, S, and Mg + S (Table 6). In 2006, the effect of P fertilizer on P_c persisted

Table 6

Phosphorus concentration in the large-size tubers in consecutive years (g kg^{-1} DM)

Treatments	Days after planting (DAP)							
	89	99	110	120	131	141	152	Y (t ha^{-1})
2006								
AC	-	-	-	1.8^{a}	2.4^{a}	2.9^{a}	2.9	29.0^{a}
NP	-	-	-	2.1^{b}	2.7^{ab}	3.1^{ab}	2.9	30.5^{a}
NPK	-	-	-	2.3^{bc}	3.0^{b}	3.3^{c}	2.9	39.2^{c}
NPKS	-	-	-	2.6^{d}	3.1^{b}	3.4^{c}	2.9	34.6^{b}
NPKSMg	-	-	-	2.5^{cd}	2.8^{ab}	3.1^{bc}	2.6	33.8^{b}
F value	-	-	-	39.5^{***}	7.5^{**}	4.9^{*}	1.6	33.7^{***}
2007								
AC	2.1	2.8^{a}	2.8^{a}	3.5^{a}	3.7	3.3	2.7	40.1^{a}
NP	2.2	2.9^{ab}	3.1^{ab}	3.8^{ab}	3.8	3.4	2.8	44.3^{a}
NPK	2.3	3.3^{ab}	3.7^{b}	4.2^{b}	3.8	3.3	2.7	64.3^{c}
NPKS	2.4	3.4^{b}	3.8^{b}	4.2^{b}	3.7	3.4	2.6	56.7^{b}
NPKSMg	2.4	3.3^{ab}	3.8^{b}	4.1^{b}	3.8	3.3	2.8	63.0^{c}
F value	0.3	4.6^{*}	8.2^{**}	4.0^{*}	0.2	2.4	0.1	70.3^{***}
2008								
AC	-	-	-	2.2^{a}	2.1^{a}	2.2^{a}	2.1^{a}	27.8^{a}
NP	-	-	-	3.0^{b}	3.1^{b}	3.5^{b}	2.7^{b}	39.5^{b}
NPK	-	-	-	2.8^{ab}	3.2^{b}	3.3^{b}	2.5^{b}	44.0^{c}
NPKS	-	-	-	2.3^{a}	3.1^{b}	3.4^{b}	2.7^{b}	53.6^{d}
NPKSMg	-	-	-	2.4^{a}	3.3^{b}	3.2^{b}	2.7^{b}	43.2^{c}
F value	-	-	-	13.4^{***}	27.9^{***}	44.5^{***}	10.1^{***}	153.7^{***}

***. **. * significant at $p < 0.001$; < 0.01; <0.05, respectively; n.s. – not significant;
[a] the same letter indicates a lack of significant differences within the treatment.

until the final maturity phase of tubers. The impact of the other nutrients on this characteristic was most striking on 120 DAP, but the effect of P fertilizer persisted until potato maturity. It was probably the cause of the highest yield on the NPK plot. In 2007, the effect of NP fertilizer compared with the AC plot was low, revealing only from 99 to 110 DAP; then it disappeared. Significantly higher P_c values were recorded in the same period in NP than in the other treatments. In 2008, the effect of NP fertilizer on P_c was most pronounced with respect to the AC plot. The effect of P fertilizer, irrespective of the year, corroborates the importance of P fertilization for P_c in tubers as a prerequisite of their high yield (Rosen, Bierman 2008).

The predictive worth of P_c in large-size tubers for yield prognosis depended on the weather pattern in a particular year of study. The regression models developed are as follows:

2006:	$Y = -3433P_c^2 + 1612P_c - 157.7$		for R^2 0.90;	
	$Y_{max} = 31.5$ t ha^{-1}		and $P_{cop} = 2.3$ g kg^{-1} DM;	
2007:	$Y = 321.9P_c - 74.0$	for $n = 5$	and $R^2 = 0.85$;	
2008:	$Y = 49.8P_c + 29.0$	for $n = 5$	and R^2 0,03, n.s;	
2008:	$Y = -151.8P_c + 85.1$	for $n = 4$	and R^2 0.62.	

The lowest yield harvested in 2006 was a result of the insufficient supply of P to large-size tubers. The main reason was the drought during stolon swelling and at the beginning of tuber expansion (June and July). In addition, a high rainfall event, which took place at the end of July, resulted in the secondary tuber growth, but without impact on its yield. The P_c in the large-size tubers in 2008 was much higher than in 2006, but the drought in May and June resulted in an unexpected response, i.e. yield drop with increasing P_c in this tuber fraction. This trend clearly indicates the dilution of P concentrations in this tuber fraction. The key reason was drought. A different trend was recorded in 2007. The concentration of P increased with the increasing tuber yield (Y), following the model:

$$P_c = -0,0002Y^2 + 0,024P - 0,287 \text{ for } R^2 = 0.97;$$
$$P_{cmax} = 4.5\% \text{ DM and } Y_{op} = 60.8 \text{ t ha}^{-1}.$$

This equation clearly indicates the limiting supply of P to the growing tubers until its concentration of 4.5 g kg^{-1} DM. The further yield increase resulted in a P_c decline, evidently stressing the occurrence of P dilution.

CONCLUSIONS

1. The phosphorus supply to potato was not a yield-limiting factor, provided favourable water conditions during the growing season. The regression models of phosphorus concentration trends in years with water shortage indicate a disturbance in P supply to potato during the growing season.

2. The fertilizer phosphorus applied together with nitrogen resulted in a significant increase in the phosphorus concentration in all potato organs.

3. The prediction of tuber yield based on the phosphorus concentration was significantly related to the plant part and the stage of potato growth. With respect to the plant part, the optimal date after planting was for: vines

– 68 and 120, small-sized tubers – 78 and 141, medium sized-tubers – 99, large-sized tubers – not consistent.

4. The phosphorus concentration in the small- and the medium-size tubers clearly indicate the shortage of P in these two tuber fractions due to the competition with the large-size potato tuber fraction.

5. The phosphorus concentration trend in large-size tubers indicates a phenomenon known as the phosphorus dilution effect. It manifested itself the earliest at the maturation stage of potato development.

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