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ORIGINAL PAPER

NITROGEN PROFILE OF POTATO DURING THE GROWING SEASON – THE TUBER YIELD PREDICTION

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Abstract

The assumption of this study was that the nitrogen (N) concentration in potato organs during the growing season is a useful tool for making prognosis of the tuber yield. This concept was validated based on data from field experiments (2006-2008) with sequentially added nutrients (0, NP, NPK, NPKS, NPKSMg) to potato. The N concentration was measured in potato vines, stolon, and the small-sized potato tubers during the crop growing season in 10-day sequences starting from BBCH 33. The seasonal pattern of N concentrations in potato organs, including tubers, was significantly dependent on the weather and modified by the applied nutrients. The nitrogen concentration in stolon + roots and in the small-sized potato tuber was much smaller compared to vines. The nitrogen concentration in vines followed a declining trend, which was described the best by the power function. It showed the predictive usefulness, based on pooled data, on 68 day after planting (DAP). The pattern of N concentrations in stolons + roots was significantly distinct for the unfertilized and fertilized plants. Its predictive value for pooled data was the strongest on 78 DAP. The N trend in the small-sized potato tuber, irrespective of the treatment, followed a 3^{rd} degree function. The yield prediction based on sets of yearly data, irrespective of the weather course, clearly showed that the best sampling date, regardless of the potato part, occurred in the early bulking stage (89 DAP).

Keywords: Nitrogen concentration, vines, stolon + roots, small-size potato tuber, regression models.

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INTRODUCTION

Potato is one of the most important sources of energy and protein for humans over the world (Camire et al. 2009). The production potential of this crop is very large, but its current exploitation by farmers is at a very low level. The yielding potential of potato in the Netherlands was determined at the level of 62.1 t ha^{-1} for the period 1976-2005, whereas in Poland it stood at 41.4 t ha^{-1}. The actual yields in the 2007-2016 period were 44.2 (±1.8) t ha^{-1} in the Netherlands and 22.6 (±3.3) t ha^{-1} in Poland (Supit et al. 2010, FAOSTAT 2018). The yield gap was 33% for the Netherlands and 45% for Poland. The difference between potential and current yields cannot be explained only by the type of climate. In fact, the Atlantic climate is more favourable for potato growers in the Netherlands than the continental climate dominant in Poland (Jongmann 2000).

The other reasons of the observed discrepancy between potential and current yields are rooted both in the natural soil fertility and production measures. In temperate regions, however, low tuber yields are mainly associated with inadequate nutrient supply and particularly, with imbalanced nitrogen-oriented fertilizer management (Jate 2010). In Poland, with respect to the former factor, potato is cultivated mostly on soils naturally poor in potassium and magnesium (GUS 2017). It is well documented in the scientific literature that this crop requires a large amount of potassium, whose content significantly affects nitrogen use efficiency (Grzebisz et al. 2017). Thus, the key challenge for potato growers is to prepare a relatively high level of available nutrients, such as P, K, Mg, and S, in order to take advantage of the yielding potential of currently grown potato varieties (Allison et al. 2000).

The main task of all nutrients both present in soil and supplied into soil by farmers is to balance nitrogen in the soil/plant system (Jenkins, Mahmood 2003, Li et al. 2015). Consequently, the efficient management of N during potato growth is required to achieve its yielding potential. The demand for N by potato fluctuates during the growing season. One of the most important challenges for both researchers and agricultural extension services is to make an adequate evaluation of the N status in the plant crop. This is motivated mainly by high in-season variability of both the biomass and N concentration of potato organs (Gayler et al. 2002). A reliable set of data is required to correct the N status in early stages of the crop growth or to make the prognosis of yield. There are numerous methods for the N status evaluation in potato, but most of the procedures apply to leaves, petioles or vines (Meyer, Marcum 1998, Goffart et al. 2008, Grzebisz et al. 2018). According to Khan et al. (2014), both the total N uptake by the crop, and the N concentration in tubers are responsible for the tuber dry yield. There is a great gap in knowledge regarding N trends during a growing season in potato organs, like stolon, and in young tubers.

This study has been undertaken to examine how the sequential input of nutrients, potentially balancing fertilizer nitrogen, influences trends in the N concentration in potato organs, including vines, stolon, and young tubers during the growing season. Another objective was to indicate the optimal sampling stage (Day After Planting) with respect to making a reliable forecast of the tuber yield based on the N concentration in a particular organ.

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 Brody Experimental Farm (Poznan University of Life Sciences, 52°44′N; 16°28′E). The field experiment was established on soil developed from loamy sand, underlain by sandy loam and classified as Albic Luvisol. The content of available nutrients in the topsoil, measured each year before fertilization, was high/very high for phosphorus (80-95 mg P kg^{-1} soil), medium for potassium (130-150 mg K kg^{-1} soil) (double lactate method), and medium for magnesium (58-62 mg Mg kg^{-1} soil) (Schachtschabel method). The amount of mineral N (N_{min}) was in the range of 23-30 kg ha^{-1} (0.01 mol dm^{-3} $CaCl_2$). Soil pH was 5.6-6.0 (1 mol dm^{-3} KCl). The meteorological data concerning precipitation showed high variability, especially in June, a month critical for potato tuberization. Water shortage appeared in June and July 2006, and in July 2008 (Figure 1).

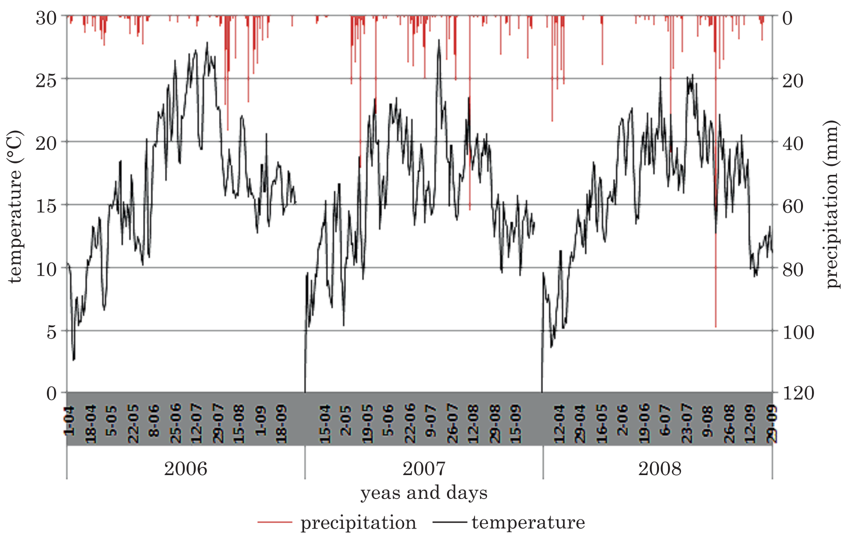

Fig. 1. Monthly mean air temperature and total precipitation at Brody Experimental Station

Experimental design

A field trial consisting of five treatments, differing in the composition of sequentially added sets of nutrients, arranged in a randomized complete block, and replicated four times, provided as the source of data for the study. 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 (K applied as Patentkali 34,9% K, 6,0% Mg, 17% S). Phosphorus in a dose of 38.7 kg P ha^{-1} was applied as di-ammonium phosphate. Potassium was applied in a dose of 166 kg K ha^{-1}. Both nutrients were applied two weeks before potato planting. The dose of S applied with SOP and Patenkali was 27.6 and 44,3 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 split and applied to potato before planting – 70 kg ha^{-1}, and 20 day after planting (DAP) – 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 with the Egner-Riehm method (PN-R-04023:1996 and PN-R-04022:1996+Az:2002); 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 determinations of nutrients 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). The nitrogen content in plant samples was determined using a standard macro-Kjeldahl procedure. Results are expressed on a dry matter basis.

Statistical analyses

The collected data were subjected to conventional analysis of variance using STATISTICA® 10 (StatSoft, Krakow, Poland). The differences between 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, stepwise regression was applied to define the 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

The in-season N course in vines

The N concentration (N_c) pattern in potato vines during the growing season was year-to-year variable (Figure 2). The highest differences between the

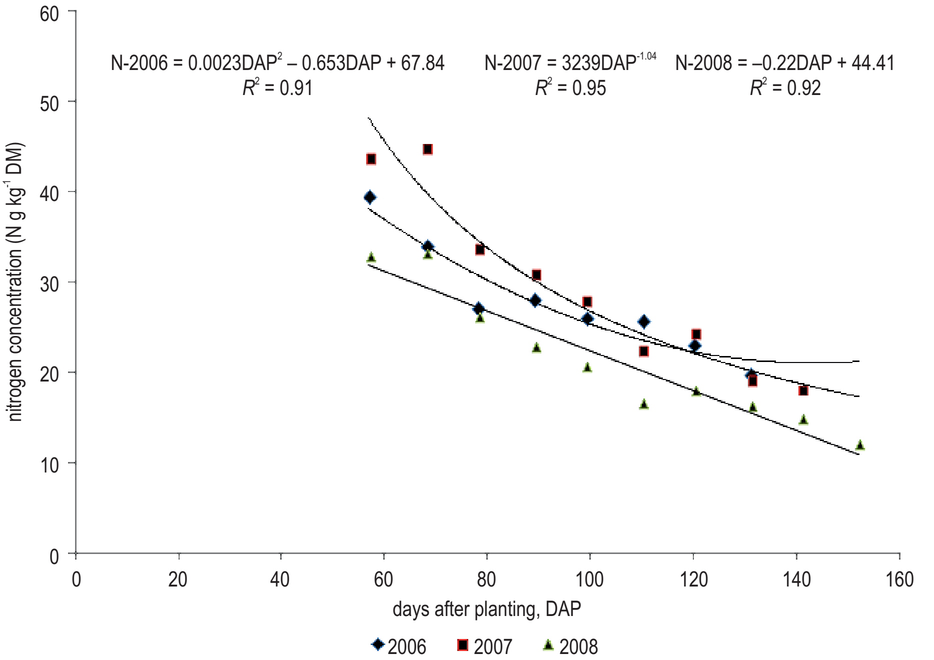

Fig. 2. Nitrogen concentration trends in potato vines in consecutive growing seasons

years were recorded at the beginning of plant growth, decreasing in the order: 2007 > 2006 > 2008. The observed patterns were described by three different regression models, which reflected the dominant type of weather in consecutive growing seasons. In the first year, i.e. 2006, the regression model obtained fitted the quadratic equation with the lowest N value of 11 g kg^{-1} DM, which was revealed on 162 DAP. This type of the N in-season variability resulted from severe drought, which lasted from May to July (Figure 1). The average tuber yield was 33.4 t ha^{-1} (in 2006), ranging from 29.3 t ha^{-1} for the control plot (AC), and to 39.1 t ha^{-1} for the NPK one (for details see Grzebisz et al. 2018). In 2007, the in-season N_c pattern followed the power function. In that year, the average tuber yield was 52.3 t ha^{-1}, but the highest yield, recorded on the NPK plot, peaked at 63.9 t ha^{-1}. The lowest N_c in potato vines during the whole growing season, following the linear regression model, was recorded in 2008. This type of N_c pattern was due to water shortage in July. The average tuber yield was 41.6 t ha^{-1} (in 2008), ranging from 28.7 (AC) to 52.6 t ha^{-1} (NPKS). A declining trend appeared for N_c

in vines, which in later stages of potato growth, irrespective of the season, is typical for potato (MUSTONEN et al. 2010). However, each of the detected N_c courses gives a completely different message for potato growers. The quadratic and linear models were indicators of water shortage. As reported by LAHLOU et al. (2003), artificially induced drought can reduce potato yield by 11 to 53%, depending on a cultivar. The optimal model of the Nc in-season course, resulting in the maximum tuber yield, was the power function. This model assumes a very high N concentration at the beginning of potato growth to be the key yielding factor. In 2007, the N concentration was by 4 g kg^{-1} higher than in 2006, and by 11 g kg^{-1} compared to 2008.

The effect of applied fertilizers on the N_c seasonal pattern was significant, but low (Table 1). The most striking differences were observed between AC and other fertilized treatments. The differences within fertilizing treatments were recorded mostly in early stages of potato growth. The early N_c

Table 1

Nitrogen concentrations in potato vines in consecutive years (g N kg^{-1} DM)

Treatments	Days after planting									
	57	68	78	89	99	110	120	131	141	152
2006										
AC	32.8^{a}	27.5^{a}	21.7^{a}	19.3^{a}	20.3^{a}	21.5^{a}	21.7^{a}	13.4^{a}	-	-
NP	41.6^{b}	35.7^{b}	22.4^{a}	20.7^{a}	20.6^{a}	22.2^{a}	24.1^{b}	22.0^{c}	-	-
NPK	41.0^{b}	35.3^{b}	29.6^{b}	26.6^{b}	20.6^{a}	23.3^{b}	23.1^{ab}	23.5^{c}	-	-
NPKS	42.7^{b}	34.4^{b}	30.9^{b}	36.9^{c}	33.4^{b}	30.6^{c}	22.8^{ab}	23.1^{c}	-	-
NPKSMg	39.3^{b}	36.9^{b}	30.9^{b}	36.6^{c}	35.3^{c}	30.7^{c}	23.3^{ab}	16.7^{b}	-	-
F value	13.6***	14.9***	110***	243***	1240***	420***	55**	118***	-	-
2007										
AC	36.8^{a}	36.3^{a}	26.3^{a}	28.9^{a}	26.6^{a}	21.2^{a}	23.2	13.1^{a}	13.5^{a}	-
NP	45.5^{b}	45.3^{b}	35.6^{b}	30.6^{ab}	28.5^{b}	23.5^{b}	24.3	21.4^{c}	16.6^{b}	-
NPK	45.0^{b}	47.3^{b}	35.1^{b}	31.7^{b}	28.0^{ab}	22.5^{ab}	25.2	23.0^{c}	14.5^{a}	-
NPKS	46.8^{b}	45.5^{b}	35.6^{b}	32.0^{b}	28.4^{b}	22.2^{ab}	24.1	22.5^{c}	22.9^{c}	-
NPKSMg	44.2^{b}	49.2^{b}	36.0^{b}	31.7^{b}	28.5^{b}	22.7^{ab}	24.9	16.3^{b}	22.9^{c}	-
F value	11.5***	18.3***	35.0***	7.5**	6.2**	5.5**	1.9	118***	104***	-
2008										
AC	29.9^{a}	26.9^{a}	25.3	21.4^{a}	19.7^{a}	15.7^{a}	17.2	16.3	10.3^{a}	11.4
NP	33.7^{b}	36.4^{b}	26.4	22.7^{ab}	21.1^{b}	17.4^{b}	18.0	16.9	11.7^{b}	12.7
NPK	33.3^{ab}	33.6^{b}	26.4	23.5^{b}	20.7^{ab}	16.7^{ab}	18.7	16.1	12.4^{b}	12.0
NPKS	34.7^{b}	35.0^{b}	26.0	23.7^{b}	21.0^{b}	16.5^{ab}	17.9	16.1	11.8^{b}	12.4
NPKSMg	32.7^{ab}	33.7^{b}	26.7	23.5^{b}	21.1^{b}	16.9^{ab}	18.5	16.1	12.2^{b}	12.2
F value	4.3*	18.3***	1.0	7.5**	6.2**	5.5**	1.9	0.9	15.2***	1.1

***. **. * 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.

status to a great extent continued to the crop maturity. In 2006, the N_c course, irrespective of the treatment, followed the quadratic regression model. The lowest N_c in potato vines recorded on 100 DAP on the AC plot was 20 g kg^{-1} DM, being higher on the NPK plot, namel 21.5 g kg^{-1} DM on 114 DAP. In the three consecutive years, the in-season N_c decreased linearly in accordance with the tuber expansion rate, yet being much lower in 2008. These two distinct models clearly suggest some disturbance in N supply to potato in years with water shortage, causing yield decline. Karafyllidis et al. (1996) found that deep water stress resulted in a 20% lower number of tubers, leading to a yield loss of 33%.

The optimal date of plant sampling for the tuber yield prediction was highly variable. The applied stepwise regression analysis, based on the pooled set of data, showed that the tuber yield depended on N concentration in vines in two particular dates, i.e. the 68th and 110th DAP. The obtained equation is:

$$Y = -1.112 + 1.86DAP68 - 1.3DAP110 \text{ for } R^2 = 0.78 \quad [1]$$

This equation clearly stresses the imbalanced N status of potato during growth. It was observed the N shortage, mainly in the early stages of potato growth, whereas it's excess at the full tuber growth period, i.e. in 110th DAP. The applied simple regression analysis underlined the fact that the N status in the 68th DAP can be used to make the first prediction of the final tuber yield. The developed equations are:

$$Y = 1.44N - 10.8 \text{ for } n = 15,\ R^2 = 0.67 \text{ and } P \leq 0.001 \quad [2]$$

$$Y = 1.58N - 13.8 \text{ for } n = 12,\ R^2 = 0.79 \text{ and } P \leq 0.001 \quad [3]$$

The N concentration in the 68th DAP was much higher in 2007 compared to other years. It stresses the importance of N nutritional status at this stage of potato growth. The yield prognosis at this stage would be much higher, provided NP treatment was excluded. This dependence evidently shows potassium as a key yield forming factor (Grzebisz et al. 2017). The detailed analysis, conducted on the annual set of data, clearly indicates a much later period, around the 89th DAP, as the most reliable for yield prediction. The strongest yield prognosis, based on yearly data was conducted just in the 89th DAP. As shown in Figure 3, it followed the linear regression model for 2007 and 2008, and a quadratic one for 2006. The latter one informs that N management by potato was significantly disturbed. The key reason was drought (Figure 1). This conclusion corroborates findings by Moulin et al. (2012), who stated that N concentration in petiole, determined at later stages of potato growth, in spite of being year-to-year variable, revealed as a good predictor of the tuber yield.

The in-season N course in stolon + roots

It has been assumed that Nc in potato stolon + roots is of the key importance for explaining crop sensitivity to N supply from soil resources.

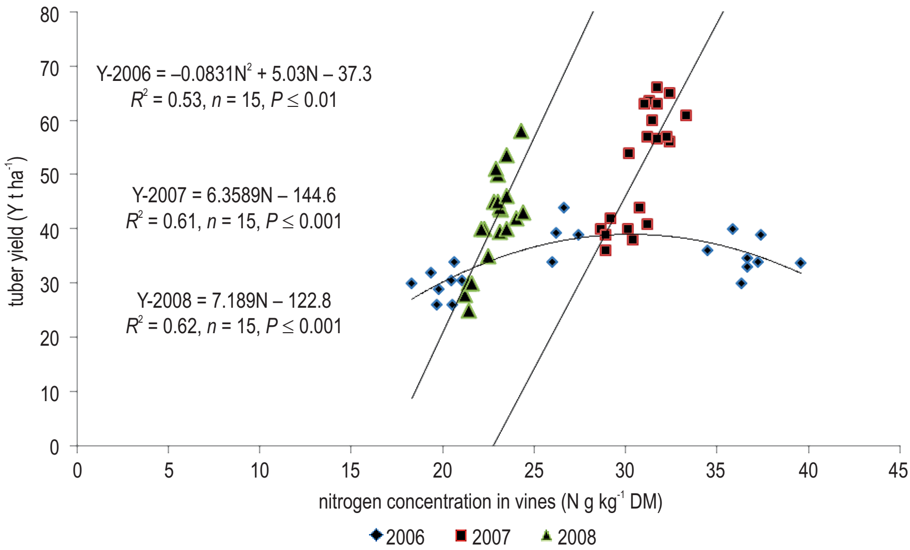

Fig. 3. Yield of tubers (Grzebisz et al. 2018) as a function of nitrogen concentration in vines

The conducted study is in accordance with Gayler et al. (2002), who stated that a reliable prediction of the tuber yield is mostly limited by lack of data on N content in all potato organs. These authors stressed that a special attention in preparing any yield prediction models should be devoted to N_c in roots, which are in direct contact with available N pool. In our study, N_c in potato stolons and roots was as a rule much lower compared to that recorded in vines (Table 2).The N_c trend during the growing season was governed by weather, being, however, modified by the applied fertilizers. The biggest N_c decline was recorded in 2006, a year with drought lasting for most of June and July. In all years, the trend of N_c fitted a 3rd degree function (Figure 4). Based on these results, inflation points (DAP_{ip}) were calculated. The developed equations clearly show that a significant change in the N_c in stolon takes place, irrespective on weather, at a specific stage of potato growth. The decrease in N_c within the period, extending from 89 to the 99 DAP was as follows: 2007 (-5.7) > 2008 (-4.2) ≥ 2006 (-3.7). The tuber yield, averaged over the fertilizing treatments, was significantly affected by the N_c change in the stolon (ΔN) within this particular period:

$$Y = 9.76\Delta N - 1.55 \text{ for } n = 3, \text{ and } R^2 = 0.98 \quad [4]$$

It has been observed that the biggest decrease in N_c occurred just in the year with ample water supply. This can be attributed to the number of tubers, which depends on the supply of N at the stage of stolon swelling (Karafyllidis et al. 1996, Gao et al. 2014).

The effect of applied fertilizers on N_c in potato stolons was the most striking within the period extending from 89 to 99 DAP. There was a significant N_c drop during this period. It equalled -0.8% for the NPK fertilized

Table 2

Nitrogen concentrations in potato stolons and roots (g N kg^{-1} DM)

Treat-ments	Days after planting									
	57	68	78	89	99	110	120	131	141	152
2006										
AC	17.2^{a}	14.0	15.6^{b}	11.4^{a}	11.7^{a}	12.7^{a}	15.5^{b}	9.6^{a}	-	-
NP	22.0^{b}	15.3	15.8^{b}	11.8^{a}	12.1^{a}	14.5^{ab}	15.7^{b}	12.2^{ab}	-	-
NPK	24.4^{b}	15.0	13.6^{a}	25.6^{b}	19.4^{ab}	16.2^{ab}	13.5^{a}	13.0^{c}	-	-
NPKS	22.1^{b}	16.8	18.1^{c}	26.0^{b}	22.8^{b}	19.4^{b}	18.0^{c}	13.4^{c}	-	-
NPKSMg	23.1^{b}	15.4	17.9^{c}	27.2^{c}	25.1^{b}	19.2^{b}	17.8^{c}	13.4^{c}	-	-
F value	21.9^{***}	0.11	28.5^{***}	821^{***}	770^{***}	4.6^{*}	28.5^{***}	21.6^{***}	-	-
2007										
AC	19.4^{a}	18.4^{a}	15.4^{a}	19.7^{a}	15.8	12.8^{a}	12.4^{a}	9.3^{a}	7.6^{a}	-
NP	24.0^{b}	20.5^{ab}	22.3^{b}	21.7^{b}	16.2	14.5^{b}	13.5^{b}	12.7^{b}	11.7^{c}	-
NPK	26.5^{b}	19.7^{ab}	23.2^{b}	22.2^{b}	16.2	14.7^{b}	14.7^{c}	13.1^{b}	10.1^{b}	-
NPKS	24.1^{b}	22.5^{b}	22.8^{b}	22.5^{ab}	16.6	15.1^{b}	14.7^{c}	13.0^{b}	13.4^{d}	-
NPKSMg	26.0^{b}	19.6^{ab}	23.0^{b}	23.6^{c}	16.5	15.2^{b}	15.1^{c}	11.9^{b}	13.3^{d}	-
F value	19.6***	3.4*	63.8***	28.9***	1.2	22.6***	48.6***	21.6***	138***	-
2008										
AC	15.8^{a}	13.7^{a}	14.9	14.6^{a}	11.7	9.5^{a}	9.2^{a}	8.5^{a}	8.6	8.1
NP	$.17.8^{ab}$	14.5^{ab}	16.6	16.1^{b}	12.0	10.8^{b}	10.0^{b}	9.4^{ab}	9.6	8.8
NPK	19.6^{b}	15.2^{ab}	17.2	16.5^{b}	12.0	10.9^{b}	10.9^{c}	8.9^{ab}	9.0	8.7
NPKS	17.8^{ab}	14.6^{ab}	16.9	16.7^{b}	12.3	11.2^{b}	10.9^{c}	10.0^{b}	9.3	8.7
NPKSMg	19.3^{b}	16.7^{b}	17.0	17.5^{b}	12.2	11.3^{b}	11.2^{c}	9.5^{ab}	9.4	8.9
F value	10.2***	3.4*	7.5**	28.9***	1.2	22.6***	48.6***	3.1*	1.1	1.1

***. **. * 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.

plants and only -0.22% for the AC ones. This difference implicitly explains differences in the tuber yield. It is necessary to stress that the N_c decrease in plants fertilized with NPKS and NPKSMg was both much lower and delayed by one sampling stage compared to those fertilized with NPK only. The observed delay was probably the key reason for considerably lower yields on treatments with additionally added S and Mg.

The analysis of the Nc course in potato stolons + roots during the growing season clearly shows the most crucial periods of yield component formation by potato. The tuber intensive growth, i.e. bulking, begins just after tuberization (Jackson 1999). This process requires a good supply of N to the growing plants. However, this cannot be achieved without an adequate supply of K (Grzebisz et al. 2017). The applied stepwise regression analysis showed that the N status in stolons measured on 78 DAP can be used to make the tuber yield prediction. The developed equation is:

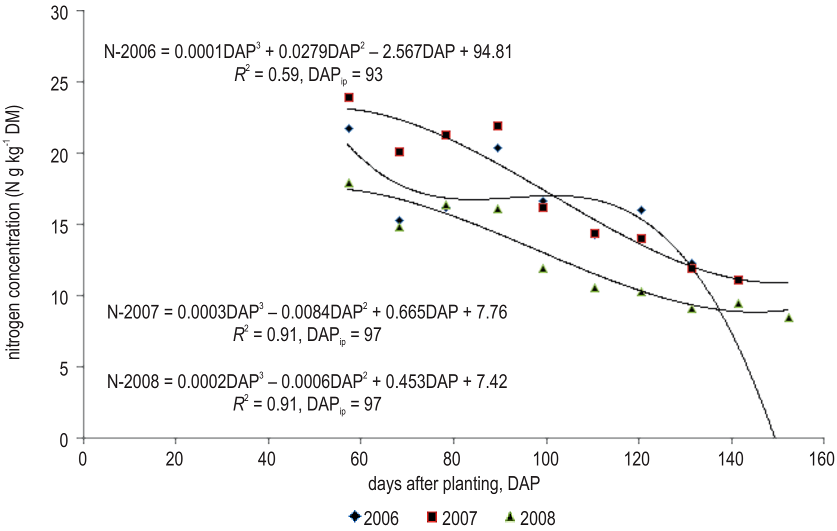

Fig. 4. Nitrogen concentration trends in potato stolon + roots in consecutive growing seasons: DAP_{ip} – inflation point for days after planting

$$Y = 2.8DAP78 - 7.62 \text{ for } n = 15, R^2 = 0.60 \text{ and } P \leq 0.001 \qquad [5]$$

However, the yield prognosis based on the yearly set of N_c data was much more reliable stronger (R^2) when conducted at a later stage, i.e. on 89 DAP (Figure 5). This date coincides with the optimum date of yield prediction based on the N concentration in vines (Figure 3). Significant relationships between N_c in stolons and the tuber yield were recorded in 2007 and 2008, but not in 2006. The linear models obtained clearly indicate a deficit of N in this plant part with respect to the tuber yield.

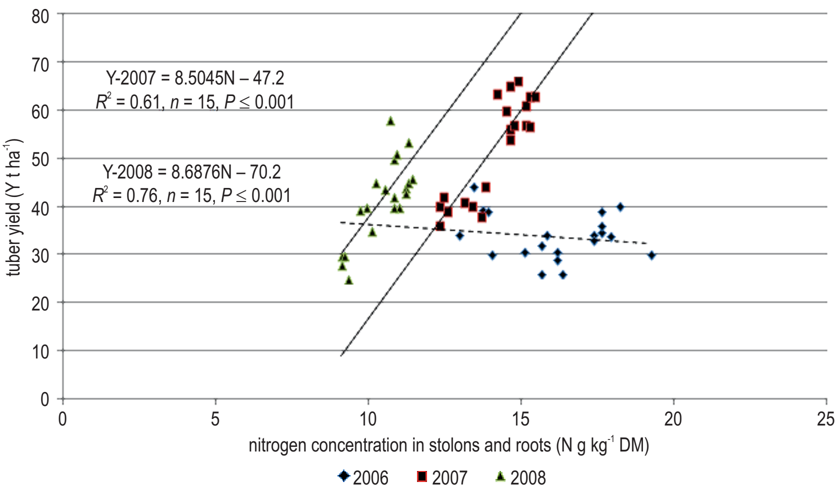

Fig. 5. Yield of tubers tubers (Grzebisz et al. 2018) as a function of nitrogen concentration in stolons and roots

The in-season N course in the small-sized tubers

The in-season N_c pattern in the small-sized potato was significantly driven by the weather (Table 3), fitting a cubic regression model, irrespective of the year (Figure 6). The initial N_c was 10 g kg^{-1}, 15 g kg^{-1}, and 11 g kg^{-1}, declining at harvest to 9 g kg^{-1}, 7 g kg^{-1} and 6 g kg^{-1} for 2006, 2007, and 2008, respectively. The biggest decrease occurred in 2007, a year with the highest yield. The key attribute of the N_c course in each of the growing seasons was its increase within the period from 78 to 89 DAP, decreasing afterwards. This uniform course of developed regression models, in spite of the seasonal variability in the weather during potato growth, is probably a natural feature of the N_c pattern in young tubers. The calculated DAP_{ip} indicates

Table 3

Nitrogen concentrations in the small-size potato tubers (g N kg^{-1} DM)

Treatments	Days after planting							
	78	89	99	110	120	131	141	152
2006								
AC	11.2^{a}	16.0^{a}	15.0^{a}	12.5	10.4^{a}	6.5^{a}	6.8	7.2^{a}
NP	11.6^{a}	17.4^{b}	14.2^{a}	13.4	11.1^{a}	8.7^{b}	7.2	9.0^{b}
NPK	10.4^{a}	18.1^{b}	17.4^{b}	17.0	14.9^{b}	11.4^{c}	7.5	9.4^{b}
NPKS	16.4^{b}	17.3^{b}	16.3^{ab}	16.5	16.3^{b}	11.9^{c}	7.1	9.1^{b}
NPKSMg	15.4^{b}	17.7^{b}	17.5^{b}	15.7	15.3^{b}	12.3^{c}	7.4	9.8^{b}
F value	25.7***	9.5***	4.6*	1.0	25.7***	111***	1.9	18.3***
2007								
AC	10.6^{a}	13.8^{a}	13.8^{a}	11.8^{a}	10.2^{a}	6.4^{a}	6.9^{a}	5.5^{a}
NP	14.7^{b}	15.1^{b}	14.4^{ab}	13.0^{ab}	11.6^{ab}	11.1^{c}	8.6^{b}	7.3^{ab}
NPK	14.9^{b}	15.3^{b}	15.0^{b}	12.4^{ab}	11.6^{ab}	11.6^{c}	7.7^{ab}	7.3^{ab}
NPKS	14.9^{b}	15.0^{b}	15.1^{b}	13.3^{b}	11.6^{ab}	12.0^{c}	12.1^{c}	7.4^{ab}
NPKSMg	15.1^{b}	15.3^{b}	14.2^{ab}	13.0^{ab}	11.4^{ab}	8.5^{b}	11.4^{c}	9.0^{b}
F value	259***	30.3***	4.6*	3.2*	7.6**	111***	37.9***	8.3***
2008								
AC	10.2^{a}	10.3	10.2^{a}	8.7^{a}	7.6^{a}	6.8^{a}	5.9^{a}	5.5
NP	10.9^{b}	11.2	10.7^{ab}	9.7^{ab}	8.6^{ab}	7.6^{b}	7.4^{b}	6.7
NPK	11.0^{b}	13.2	11.1^{b}	9.2^{ab}	8.6^{ab}	7.7^{b}	6.3^{ab}	6.2
NPKS	11.0^{b}	11.1	11.2^{b}	9.9^{b}	8.6^{ab}	7.8^{b}	6.7^{ab}	6.4
NPKSMg	11.2^{b}	11.4	10.5^{ab}	9.6^{ab}	8.4^{ab}	7.7^{b}	7.0^{ab}	6.3
F value	16.1***	1.6	4.6*	3.28	7.6**	13.8***	3.4*	1.7

***. **. * 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.

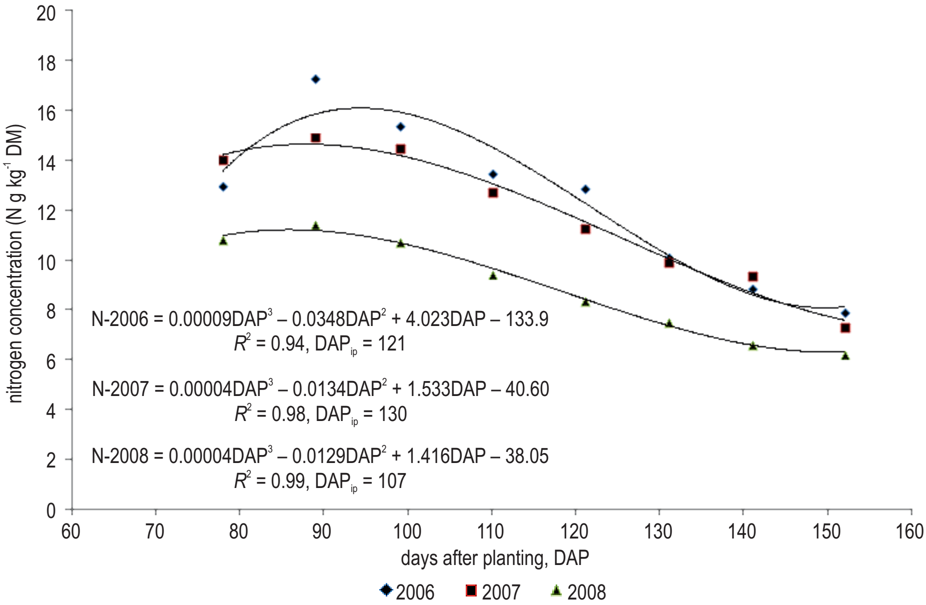

Fig. 6. Nitrogen concentration trends in the small-size tubers in consecutive growing seasons: DAP_{ip} – inflation point for days after planting

a day in which the N_c drop in the small-sized tubers was significantly delayed with respect to its maximum. This period was the longest in 2007, resulting in the highest tuber yield.

The applied fertilizer treatments resulted in a significantly higher N_c in the small-sized tubers compared to the absolute control. This notwithstanding, the general pattern of N_c course was the same. The impact of the weather was more pronounced on unfertilized plots than on those fertilized with NPK. The stepwise regression analysis showed that the prediction of the tuber yield requires data on N_c in three stages such as 99, 110 and 152 DAP. The equation obtained is:

$$Y = -19.8 + 7.0DAP99 – 6.4DAP110 + 7.23DAP152 \text{ for } R^2 = 0.77 \quad [6]$$

This equation clearly stresses that N_c increase in the small-sized tubers on 110 DAP resulted in a lower potato yield. The detailed analysis, taking into account year-to-year variability, evidently stressed the predictive value of 89 DAP (Figure 6). This date coincides with the one observed for vines and stolons + roots (Figures 3 and 5). On 89 DAP, predictibility corroborated by R^2 reached 0.61. It was linear in 2006 and 2007, but quadratic in 2008. For this particular year, the best prediction was obtained 10 days later, i.e. on 99 DAP:

$$Y = 20.3DAP – 175.5 \text{ for } n = 5, R^2 = 0.76, \text{ and } P \leq 0.01 \quad [7]$$

This equation shows that the N supply to potato crop in 2008 was retarded due to the shortage of water, resulting in slower N supply to growing tubers. This delay was the key reason for the yield decline compared to 2007.

CONCLUSIONS

1. The tuber yield prediction can be made based on nitrogen concentrations in vines, stolon + roots, and young tubers.

2. The nitrogen concentrations in stolon + roots, and in young tubers were much lower than in vines.

3. The N trend in all potato parts was, in general, significantly dependent on the weather. For vines, stolon + roots, the linear regression model coincided with the highest yield of tubers.

4. The pooled data of N concentrations in vines clearly indicates the beginning of stolon swelling (68 DAP) as the date of the first prediction of the tuber yield. The reliability of yield prognosis increases under conditions of good supply of nutrients, including potassium, magnesium, and sulfur.

5. The pooled set of data for the N concentration in stolons + roots clearly indicate the beginning of tuber growth (78th DAP) as the best date for prediction of the tuber yield.

6. The change in the N concentration in stolon + roots, which took place, irrespective of weather and fertilizing treatments, at the defined stage of potato growth during the period from 89 to 99 Days After Planting is crucial for potato bulking.

7. The slow rate of a decrease in the N concentration in the small-sized tubers with respect to its maximum can be considered as a prerequisite of a high yield of tubers.

8. The yield prediction based on yearly data, irrespective of the weather course, clearly showed that the best sampling date, regardless of which potato part was analyzed, was the beginning of tuber growth (89 DAP).

REFERENCES

Allison M.F., Fowler J.H., Allen E.J. 2001. *Response of potato (Solanum tuberosum* L.*) to K fertilizers*. J. Agric. Sci., 136: 407-426. DOI: 10.1017/S0021859601008863

Camire M.E., Kubov S., Donnelly D.J. 2009. *Potatoes and human health*. Crit. Rev. Food Sci. Nutr., 49: 823-840. DOI: 10.1080/10408390903041996

FAOSTAT 2018. Food and Agriculture Organization of the United Nations. http, //faostat.fao.org/site/567/default.aspx#ancor. Available online, accessed 2018-09-05.

Gayler S., Wang E., Priesack E., Schaaf T., Maidl F.-X. 2002. *Modelling biomass growth, N-uptake and phenological development of potato crop*. Geoderma, 105: 367-383. DOI: 10.1016/ /S0016-7061(01)00113-6

Goffart J.P., Olivier M., Frankinet M. 2008. *Potato crop nitrogen status assessment to improve N fertilization management and efficiency, past-present-future*. Potato Res., 51: 355-383. DOI: 10.1007/s11540-008-9118-x

Gao Y., Jia L., Hu B., Alva A., Fan M. 2014. *Potato stolon and tuber growth influenced by nitrogen form*. Plant Prod. Sci., 17(2): 138-143. DOI: 10.1626/pps.17.138

Grzebisz W., Čermák P., Rroco E., Szczepaniak W., Potarzycki J., Füleky G. 2017. *Potassium impact on nitrogen use efficiency in potato – a case study from the Central-East Europe*. Plant Soil Environ., 63(9): 422-427. DOI: 10.17221/344/2017-PSE

Grzebisz W., Potarzycki J., Biber M. 2018. *The early prognosis of tuber yield based on nitrogen status in potato tops*. Plant Soil Environ., 64(11): 539-545. DOI: 10.17221/388/2018-PSE

GUS 2017. *Statistical Yearbook of Agriculture*. Central Statistical Office, 495 p.

Jackson S.D., 1999. *Multiple signaling pathway control tuber induction in potato*. Plant Physiol., 119: 1-8. DOI: 10.1104/pp.119.1.1

Jenkins P.D., Mahmood S. 2003. *Dry matter production and partitioning in potato plants subjected to combined deficiencies of nitrogen, phosphorus and potassium*. Ann. Appl. Biol., 143: 215-229. DOI: 10.1111/j.1744-7348.2003.tb00288.x

Jate M. 2010. *Long-term effect of balanced mineral fertilizer application on potato, winter rye, and oat yields; nutrient use efficiency and soil fertility*. Arch. Agron. Soil Sci., 56(4): 421-432. DOI: 10.1080/03650340903512579

Jongmann R.H.G., Bunce R.H.G., Metzger M.J., Mucher C.A., Howard D.C., Mateus V.L. 2006. *Objectives and applications of a statistical environmental stratification of Europe*. Landscape Ecol., 21: 409-419. DOI: 10.1007/s10980-005-6428-0

Karafyllidis D.I., Stavropoulos N., Georgakis D., Karafyllidis D.I, Stavropoulos N., Georgakis D. 1996. *The effect of water stress on the yielding capacity of potato crops and subsequent performance of seed tubers*. Potato Res., 39(1): 153-163. DOI: 10.1007/BF02358215

Khan M., Yin X., Van Der Putten P.E.L., Struik P.C. 2014. *An ecophysiological model analysis of yield differences within a set of contrasting cultivars and f1 segregating population of potato (Solanum tuberosum L.) grown under diverse environment*. Ecol. Model., 290: 146-154. DOI: 10.1016/j.ecolmodel.2013.11.015

Lahlou O., Ouattar S., Ledent J-F. 2003. *The effect of drought and cultivar on growth parameters, yield, and yield components of potato*. Agronomie, 23: 257-268. DOI: 10.1051/agro:2002089

Li S., Duan Y., Guo T., Zhang P., He P., Johnston A., Shcherbakov A. 2015. *Potassium management in potato production in Northwest region of China*. Field Crops Res., 174: 48-54. DOI: 10.1016/j.fcr.2015.01.010

Meyer R.D., Marcum D.B. 1998. *Potato yield, petiole nitrogen, and soil nitrogen response to water and nitrogen*. Agron. J., 90(3): 420-429.

Moulin A.P., Cohen Y., Alchanatis N., Tremblay N., Volkmar K. 2012. *Yield response of potatoes to variable nitrogen management by landform element and in relation to petiole nitrogen – a case study*. Can. J. Plant Sci., 92: 771-781. DOI: 10.1139/CJPS2011-005

Mustonen L., Wallis E., Hurme T. 2010. *Nitrogen fertilization and yield formation of potato during a short growing period*. Agric. Food Sci., 19: 173-183.

Supit I., Van Diepen C.A., De Wit A.J.W., Kabat P., Baruth B., Ludwig F. 2010. *Recent changes in the climatic yield potential of various crops in Europe*. Agric. Sys., 103: 683-694. DOI: 10.1016/j.agsy.2010.08.009