ACCUMULATION OF NITROGEN, PHOSPHORUS AND POTASSIUM IN MATURE MAIZE UNDER VARIABLE RATES OF MINERAL FERTILIZATION

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Abstract. A field study was carried out on maize in 2007–2011, with the aim to determine the effect of differentiated phosphorus and potassium fertilization rates on N, P, and K contents in maize organs as well as accumulation of these nutrients at maize physiological maturity. A single-factor experiment was established in a randomized complete block design with 4 replications for each treatment. The obtained results showed that the experimental factor significantly varied macronutrient contents in the analyzed maize organs. Mineral fertilization significantly increased N concentration when compared to the control. Significant effects of the experimental factor on the differences between the treatments with regard to phosphorus and potassium contents were found, nonetheless, when compared to the control, nutrient increase was not observed in all the organs examined. An especially strong maize response to the absence of potassium fertilization or application of different rates of this element was observed in maize stems, leaves and husks. The form of phosphorus applied as fertilizer showed no significant effect on P contents in the maize organs, as well as on the total accumulation of this nutrient in the plant. Percentage shares of grain accumulated nutrients in the total nutrient accumulation in the aboveground biomass showed significant differentiation as a result of P and K fertilization. For the most part, nitrogen and phosphorus were accumulated in maize grain (60–70%), and potassium – in the stems (50–61%). Regardless of the treatment examined, regression analysis showed that maize yields were determined by the total accumulation of nitrogen.

Key words: maize, nutrient harvest index, nutrient uptake, physiological maturity

INTRODUCTION

During the last decade, maize has turned out to be a crop plant cultivated in Poland on dynamically expended areas. An enhanced interest in maize cultivation is associated with utilization of this crop as renewable energy resource, among others – in biofuel production. Maize is characteristic of a very high yield potential, expressed both by plant biomass and grain yields [Potarzycki 2010a]. Among the factors limiting the amount of possibly obtainable yield, there are frequently highlighted those with regard to plant specific requirements, such as water accessibility and mineral nutrient imbalance. Maladjustment of the fertilization system to plant quantitative needs, and especially to nutrient uptake dynamics in grain-field crops, results in disturbances in the functions of individual nutrients, low rates of their utilization by plants as well as an increased risk of environment pollution [Öborn et al. 2005, Roberts 2008]. The fulfillment

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of the fundamental goal of maize fertilization, i.e. obtaining high and stable yields, requires a suitable supply of P and K at every growth stage of the plant, maintained at a level with no impedimental effects. Optimization of maize nutrition is essential to maintain the production of high quality yield [Zhang et al. 2007]. The tools to diagnose crop P status have become ever more important to minimize the risk of surface and groundwater contamination, owing to excessive fertilization on the one hand, and on the other – application of ample P rates for the best possible yield [Iho and Laukkanen 2012]. In many prosperous countries, phosphorus overload as a result of excessive use of fertilizers is perceived as an acuter environmental problem than those concerning P constraints and greater than ever costs of phosphorus fertilization [Abel et al. 2002]. In support of the maximum crop response, phosphorus needs adequate potassium levels as well as prospective P–K interactions in plant uptake [Çelik et al. 2010]. [Smil 1999] points out that in contrast to nitrogen and phosphorus, potassium fertilizers are applied at much lower rates, and less than 50% of potassium removed by crops is replenished. The effect of phosphorus and potassium on yields largely stems from the functions of these elements in lessening the influence of biotic and abiotic stress factors. The plants well nourished with P and K better withstand water deficit and low temperatures, and are more resistant to pathogenic agents [Ma et al. 2006, Zörb et al. 2014]. During plant growth, efficient water management is conditioned by adequate nutrition with potassium. Physiological analyses showed, that inhibition of plant growth (precisely, that of plant somatic cells) was the first, direct symptom of unsatisfactory potassium supply. Visible signs of K deficiency are reflected in undersized plants in grain-fields, often with leaf chlorosis. Recent studies have shown higher K contents in chlorotic plant parts [Çelik et al. 2010, Torres et al. 2006]. The status observed is not just the effect of direct potassium action, because an additional stress factor is indirectly involved in the process, i.e. insufficient supply of nitrogen and iron. Plant functioning depends on balanced fertilization with all macro- and micronutrients. The nutrients hardly ever act separately. Nutrient interactions can have both of synergistic and antagonistic character. The interactions can either enhance or reduce nutrient uptake and utilization. Numerous studies showed, that the interaction between nitrogen and other nutrients in the first place affect plant yields and nitrogen utilization [Fixen et al. 2005, Roberts 2008]. Leigh and Wyn [1984] reported that adequate K supply is needed to maintain N metabolism.

Up to date knowledge on maize response to phosphorus and potassium supply allows to assume the following hypothesis: the accumulation of nitrogen (N), phosphorus (P) and potassium (K) by maize specifies a changeable reaction to pre-seeding fertilization with phosphorus and potassium. The aim of the present study was to assess nutrient contents in maize organs as well as their accumulation in this crop at the stage of physiological maturity, under differentiated rates of mineral fertilization with P and K.

MATERIAL AND METHODS

During 5 subsequent vegetation seasons (2007–2011), in the Wieszczyczyna agricultural holding, situated in close proximity to the Śrem city (central Poland, 52°02′ N, 17°05′ E), there was conducted an exact field experiment on 'Veritis' maize variety. The single-factor experiment was established in the randomized complete block design with 4 replications for each treatment. The experiment was a part of the long-term study undertaken in 2000. The soil with acidic reaction (pH KCL 4.9) was characterized by medium contents of available phosphorus, potassium and magnesium. The experimental factor tested was the differentiated rate of mineral fertilization with phosphorus and potassium. The doses of phosphorus and potassium were ad-

justed to 25% (W25) and 50% (WP50, WK50) with reference to the treatment with optimally balanced nitrogen (W100). The level of P fertilization in the latter was 26 kg P·ha⁻¹, with the exception of the year 2007, when 35 kg P·ha⁻¹ was applied. Depending on the observation year, potassium rates ranged from 100 kg K·ha⁻¹ (2007) to 133 kg K·ha⁻¹ (2009). During the other vegetation seasons observed, there was applied 125 kg K·ha⁻¹. The control treatments were fertilized with constant nitrogen and magnesium rates, and there was neglected fertilization with P (WPN) or K (WKN). In W100-PAPR treatment, there was applied partially acidulated phosphate rock as an alternate source of phosphorus in single superphosphate. Phosphate rock used in the study contained 10.2% of P and its acidification was 50% (i.e. sulfuric acid amount utilized during the technological process for obtaining the product was 50% of the amount necessary for the production of single superphosphate). All other treatments were fertilized with phosphorus in the form of single superphosphate, potassium as potassium salt (60% K_2O) and nitrogen as ammonium nitrate. The source of magnesium was kieserite (27% MgO), applied at a rate 16 kg Mg·ha⁻¹. Depending on the observation year, nitrogen was added at a rate 120 kg N·ha⁻¹ or 150 kg N·ha⁻¹, and these were split into 2 doses (70% before plant seeding and 30% at the stage of 4 fully unfolded leaves). Detailed description of methodology is presented by Bąk and Gaj [2016].

Plant yield and N, P and K concentrations were assessed every year study of the study. Maize grain yield was determined in plants harvested manually from two adjacent central rows (16 m long). Details on maize yields obtained are provided in the paper by Bąk and Gaj [2016]. During nutrient concentration assessments, 5 maize plants were randomly chosen (on each treatment) and divided into the sets of leaves, stems, husks, grain and cob cores. Plant samples were dried out at 65ºC to the constant weight and ground for further analyses. Nitrogen concentration in the plant material was determined by the Kjeldahl method (Auto Distillation unit Kjeltec 2200 FOSS). P and K concentrations were assessed in ground plant material and mineralized at 550ºC for 6 hours. Next, the ash obtained was mixed with 2cm³ of diluted HNO_3 (concentrated nitric acid and distilled water 1:1). Phosphorus was determined calorimetrically with vanadium-ammonium molybdate. Potassium concentration was assessed by the FAAS method (Flame Atomic Absorption Spectrophotometry, Varian 250 plus). Nutrient uptake was calculated based on dry weight values multiplied by nutrient concentration in plant organs (information on dry weights available from the authors). Nutrient harvest indexes (NHI, PHI, KHI) were calculated based on the algorithms concerning relations between nutrient accumulation in maize grain and the total nutrient accumulation in maize plant at the stage of physiological maturity. Unit nutrient uptake has been calculated by dividing total amount uptake of N, P and K respectively by grain yield of maize.

The effect of the experimental factor on nutrient accumulation and concentration under differentiated mineral fertilization with P and K was tested with 2-way ANOVA (mixed-effects model).

The symbol y_{ij} expressed the estimated value of the variables (concentration of nutrients examined in plant organs, nutrient accumulation and the specific rate of nutrient uptake) coming from analyzed *i*-observation year (i =1,…,5) at *j* different fertilization treatments (j = 1,…,8) [Caliński et al. 1987].

The mixed-effects model in 2-way ANOVA including interactions of the factors was as follows for random factor A and constant factor B:

$$y_{ij} = \mu + \alpha_i + \beta_j + \left(\beta\right)_{jk} + e_j$$

where:
μ – grand mean
α_i – is the effect of *i*-th year

$ß_i$ – is j-th fertilization treatments
$(αß)_{ij}$ – A and B interaction effect at $α_iß_j$

The Tukey's test (multiple comparison procedure) was used for comparing mean macro-nutrient concentrations under different fertilization treatments and splitting up the set of mean values into homogenous groups [Kala 2002].

When independent (predictor) variables are correlated, a one step procedure is of no use in determination of independent variables that should be included in the regression model. This means, that it is necessary to apply another method allowing to establish the best set of independent variables. Cause-result relationships between the parameters analyzed were tested by means of multiple regression. The regression model was built based on stepwise regression with bidirectional elimination, testing at each step for variables to be included or excluded. In this way, crucial variables deciding about the yield obtained were determined.

The goal of stepwise regression is to include the minimum set of independent variables in the model, and at the same time, to maximize the determination coefficient and to minimize mean squared error in regression analysis.

RESULTS AND DISCUSSION

At maize physiological maturity, nutrient concentrations were analyzed in maize grain, stems, leaves, husks and cob cores. The concentrations of nitrogen, phosphorus and potassium in these organs analyzed were significantly differentiated as a result of different P and K fertilization rates, depending on the nutrient and organ analyzed (Table 1 and 2). The fertilization treatments applied to maize had no definite effect on the concentration of the nutrients observed.

Table 1.   Effect of experimental factor on nutrient concentration in maize ear (grain, cob core, husks) g·kg^{-1} D.M. (mean 2007–2011)

Treatments	Maize parts								
	Grain			Husk leaves			Cob core		
	N	P	K	N	P	K	N	P	K
Control*	13.4 c	2.32 ab	3.54 ab	4.96 a	0.72 a	5.80 ab	5.52 a	0.41 a	9.24 a
WPN	15.3 ab	2.33 ab	3.75 a	1.25 a	0.66 a	7.14 a	5.73 a	0.34 a	8.04 a
WKN	15.1 ab	2.36 ab	3.47 ab	4.93 a	0.63 a	5.18 b	5.54 a	0.41 a	9.17 a
W25	15.3 ab	2.49 a	3.70 a	5.12 a	0.67 a	6.13 ab	5.79 a	0.33 a	7.83 a
WP50	15.7 a	2.25 ab	3.68 a	5.19 a	0.79 a	6.56 a	5.71 a	0.32 a	9.09 a
WK50	15.7 a	2.25 b	3.28 b	5.32 a	0.64 a	5.95 ab	5.60 a	0.32 a	9.39 a
W100	15.5 a	2.29 ab	3.53 ab	5.08 a	0.88 a	6.06 ab	5.30 a	0.35 a	8.45 a
W100 P as PAPR	14.2 bc	2.25 b	3.47 ab	4.97 a	0.61 a	6.16 ab	5.89 a	0.40 a	7.96 a

*Control – no fertilizer application in 2007–2011; WPN – no phosphorus fertilization, optimal fertilization N, K, Mg; WKN – no potassium fertilization, optimal fertilization (N, P, Mg); W25 – 25% of PK recommended rate as compared to optimally fertilized treatment; WP50 and WK50 – 50% of P or K respectively recommended rate as compared to optimally fertilized treatment; W100 – 100% of P and K recommended rate, treatment optimally balanced with regard to nitrogen; W100 PAPR – phosphorus applied as partially acidulated phosphate rock (PAPR)

Table 2.   Effect of experimental factor on nutrients concentration in vegetative maize parts, g·kg⁻¹ (mean 2007–2011)

Treatments	Maize parts					
	Stem			Leaves		
	N	P	K	N	P	K
Control	5.55 a	1.31 c	22.6 bc	9.75 c	1.52 a	4.55 b
WPN	5.73 a	1.66 abc	26.6 ab	12.2 a	1.31 a	6.54 a
WKN	5.78 a	1.54 abc	18.5 d	11.9 ab	1.32 a	4.74 b
W25	5.78 a	1.42 bc	21.7 cd	12.4 a	1.33 a	5.80 ab
WP50	5.71 a	1.44 bc	26.3 ab	10.4 bc	1.38 a	5.67 ab
WK50	6.18 a	1.96 a	25.9 ab	10.3 bc	1.51 a	5.67 ab
W100	5.59 a	1.80 ab	27.8 a	11.2 abc	1.43 a	5.93 ab
W100 P as PAPR	6.03 a	1.64 abc	24.4 abc	11.7 ab	1.64 a	6.54 a

Treatments – explanation as in Table 1

Mineral fertilization resulted in an increase of nitrogen observed in all the organs analyzed when compared to the control. Significant differences in N concentrations in maize grain and leaves were observed between the fertilized treatments. Maize grain and leaves showed the highest N contents and considerable differentiation owing to the influence of the experimental factor. Regardless of the treatment applied, N concentration in maize grain was above the threshold value (12.6 g·kg⁻¹) determined by Liang et al. [1996]. In other plant organs examined (stems, husks, cob cores), N concentrations were comparable, with an increasing trend observed in all the fertilized treatments when compared to the control.

Phosphorus concentration in the maize organs analyzed was decreasing in the following order: grain> stems > leaves> husks>cob cores. Significant differences in P concentrations as a result of the effect of the experimental factor were observed in maize grain and stems. Regardless of the organ analyzed, no significant differences were observed in P concentration dependant on the form of phosphorus used in fertilizer applied. Differentiated fertilizer rates had no conclusive effect on differences in phosphorus concentrations in the organs analyzed with respect to the treatments applied. The concentration of phosphorus in maize grain was differentiated depending on both P and K rate applied and ranged narrowly from 2.24 to 2.48 g·kg⁻¹. In maize grain, when compared to the control, the highest increase of P concentration was observed only in the treatment with the minimal phosphorus and potassium rates (W25). Analogous relationships between phosphorus fertilization and its contents in grain was observed in wheat [Gaj and Górski 2014, Gaj and Rębarz 2014] as well as in maize [Bêlanger et al. 2011, 2012]. Up to date, numerous studies have been carried out on P concentration in corn kernels, however information on the critical concentration of this nutrient has been so far unavailable. Furthermore, no study results on P concentrations concerning the whole plant intended for fodder valuation have been published [Gautam et al. 2011]. Numerous studies indicate weak yield-forming response of maize to phosphorus fertilization as well as no relationship between P fertilization and plant P concentration [Al-Kaisi and Kwaw-Mensah 2007, Olczyk et al. 2003]. This implies a strong need to adjust fertilizer rates for soils with high P availability, bearing in mind other factors with decisive effects on plant needs with regard to phosphorus, such as weather course in the

vegetation season, plant growth environment and agricultural techniques [Gaj 2008]. Studies by Kamara et al. [2008] showed no significant relationships between phosphorus rates applied and its concentration in soybeans, however, significant differences were found in maize cultivated after soybeans in the same sites. Carsky et al. [2000] reported that P application significantly increased soybean root dry matter and root length density, which might improve soil structure, and consequently enhance water and nutrient utilization by maize and higher grain yield. In the present study, P concentration in the stems was the highest in WK50 treatment – significantly different from the control as well as W25 and WP50.

Sufficient supply of other nutrients to plants is another essential factor decisive of the concentration of a given nutrient in the plant. The ratio of N and P could be used for a posteriori diagnostics of P and N deficiencies to adjust maize crop fertilization. The nutritional status of plant with regard to nitrogen decides about phosphorus uptake. What is more, these two nutrients are involved in the processes of photosynthesis, protein biosynthesis and N_2 bonding. In the present study, N: P ratio in maize grain was significantly differentiated under the influence of the experimental factor and ranged from 5.89 (control) to 7.18 (WP50) (Table 3). Bêlanger et al. [2012] points out that grain N: P ratio below 4.0 increases the risk of maize yield reduction. Correlation analysis performed in this study proved a significant relationship between maize yield and N:P ratio in grain (0.589). Greenwood et al. [2008] and Sadras [2006] showed a significant N:P ratio increase only when grain concentrations of N and P were divergently affected by N fertilization. Sadras [2006] studied N:P ratio in cereals and showed that in more than 40% of the maximum yield plants, N:P ratio ranged narrowly, from 4.0 to 6.0. Interactions between nitrogen and phosphorus have been described in numerous studies [Sadras 2006, Skowrońska and Filipek 2010, Ziadi et al. 2007]. Rychter and Randall [1994] underline that prolonged phosphorus deficiency in the plant reduces the pool of ATP and other high energy compounds, and as a result, there decreases uptake of nitrate nitrogen ($N-NO_3$). On the other hand, nitrogen excess at phosphorus shortage causes the first symptom of P deficiency. Regarding field conditions, there still remains an important question on N and P interactions and the improvement of nutrient utilization by plants. There should be also taken into account that nitrogen-phosphorus

Table 3.   Effect of experimental factor on nutrients harvest index (HI) and unit nutrients uptake (mean 2007–2011)

Treatments	Unit uptake of nutrients*, kg·t⁻¹			Nutrient harvest index (%)			N/P
	N	P	K	NHI	PHI	KHI	
Control	19.8 b	3.41 a	16.7 bc	67.6 bc	68.2 ab	22.4 bc	5.89 c
WPN	22.4 a	3.62 a	19.1 a	68.1 abc	66.1 abc	20.7 c	6.67 abc
WKN	22.2 a	3.51 a	14.8 c	68.6 abc	68.0 ab	27.2 a	6.57 abc
W25	21.8 a	3.53 a	15.2 c	70.0 ab	71.2 a	25.7 ab	6.22 bc
WP50	22.3 a	3.39 a	18.1 ab	70.1 ab	67.0 abc	19.9 c	7.19 a
WK50	22.6 a	3.75 a	18.8 ab	69.1 abc	61.4 c	20.9 c	7.03 ab
W100	21.8 a	3.56 a	18.5 ab	71.3 a	64.9 bc	20.3 c	6.90 ab
W100 P as PAPR	21.5 a	3.57 a	17.9 ab	66.4 c	63.5 bc	20.5 c	6.36 abc

Treatments – explanation as in Table 1
* kg per 1t of grain, including concomitant amount of nutrient in vegetative parts, kg·t⁻¹

interaction processes are influenced to a great extent by soil and climatic conditions [Summer and Farina 1986].

Potassium concentration in maize differed depending on the organ analyzed and decreased with the following order: stems> cob cores> husks > leaves> grain. Significant differences were observed in K concentration in plant organs as the effect of the experimental factor. Especially strong response of maize to no K fertilization (WKN) and differentiated rates of K applied was reflected in the stems and leaves (Table 1 and 2). Potassium concentration in grain showed a stronger relationship with phosphorus fertilization than that with potassium fertilization. The highest K content in maize grain was found in no P fertilization treatment (WPN). The lack of any relationship between increasing K contents in the soil and the concentration of this nutrient in maize grain was also observed by other authors [Bruns and Eberhard 2006]. According to Leigh and Johnston [1983], low nutrient content in the plant is a poor indicator of soil potassium availability. Askegaard et al. [2004] emphasizes that complementary to soil tests evaluation of potassium in plants is a key element of effective management of this nutrient. Both, deficiency and excess of mineral elements in cereal grains decrease their biological value, and as a consequence can negatively affect metabolic processes in animals and humans [Gondek 2012]. Every process or agricultural technique with disturbing effects on plant nutrition with potassium decreases plant metabolic activity, and at the same time – adds to the reduction of nitrogen efficiency. Vyn et al. [2002] point out that potassium contents in maize organs are significantly differentiated by cultivation techniques and potassium application mode.

The total accumulation of nitrogen, phosphorus and potassium was significantly differentiated by the experimental factor (Fig. 1–3). The lowest values of uptake of the analyzed nutrients were found in the control treatment. Regardless of the treatment applied, there was observed a significant increase of nutrient accumulation as the effect of mineral fertilization. The total nitrogen uptake in fertilized treatments ranged from 161 kg N·ha^{-1} to 179.2 kg N·ha^{-1}. A consid-
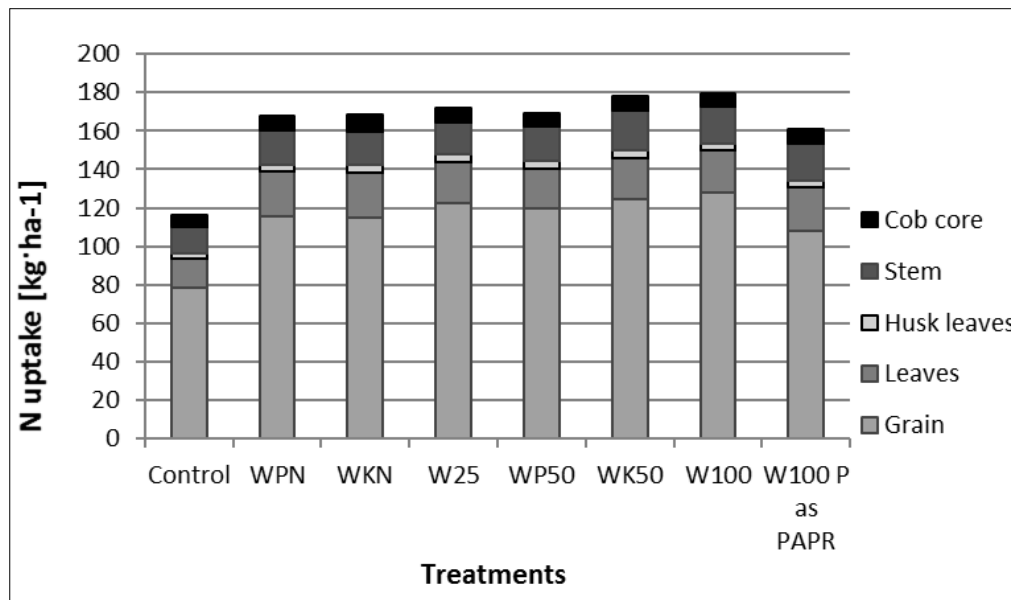

Fig. 1. Structure of nitrogen accumulation in maize at physiological maturity (BBCH 87) (mean 2007–2011)

erable portion of nitrogen taken by maize was accumulated in grain (Fig. 1). Percentage share of nitrogen accumulated in maize grain in the total accumulation of this nutrient in aboveground biomass is defined in subject literature as the nitrogen harvest index NHI. In the present study, NHI values ranged from 66 to 71% and significantly differed, depending on P and K fertilization levels (Table 3). At the same time, significant differences in NIH values were observed with reference to the source of phosphorus applied. Application of PAPR (W100 PAPR) resulted in significantly lower accumulation of phosphorus in maize grain when compared to that in the treatment with single superphosphate (W100). Yield size is shaped by the amount of phosphorus accumulated in the plant during the vegetation season and its distribution between plant organs. Yield diagnostics is based on the assessment of the final N accumulation in the plant and the index of N distribution between harvested and other plant organs [Sinclair 1998]. This was confirmed by correlation analysis performed in this study, with regard to the relationships between leaf and grain N concentrations, which showed highly significant relationships in all the treatments tested (0.867). In the period of maize generative development, the basic source of nitrogen is its stock earlier accumulated in the plant (mainly in the leaves and stems). Next, nitrogen compounds are hydrolyzed and translocated into maize grains [Grzebisz 2012]. The optimal growth conditions for grain-field crops are secured by adequate availability of nitrogen during their vegetative growth.

Accumulation of phosphorus as plant response to increasing P in fertilizer rates was significantly different in W100, WK50 and WP50 treatments (Fig. 2). Other experimental treatments did not significantly differed from each other. Phosphorus harvest index (PHI) value was the lowest in WK50 treatment, and significantly differed from other treatments examined. The highest PHI value was found in W25 treatment. Accumulation of phosphorus in grain increased with decreasing P rate in the fertilizer applied. High efficiency of P fertilization depends not only on phosphate uptake from the soil, but also on nutrient translocation between plant organs [Sattel-
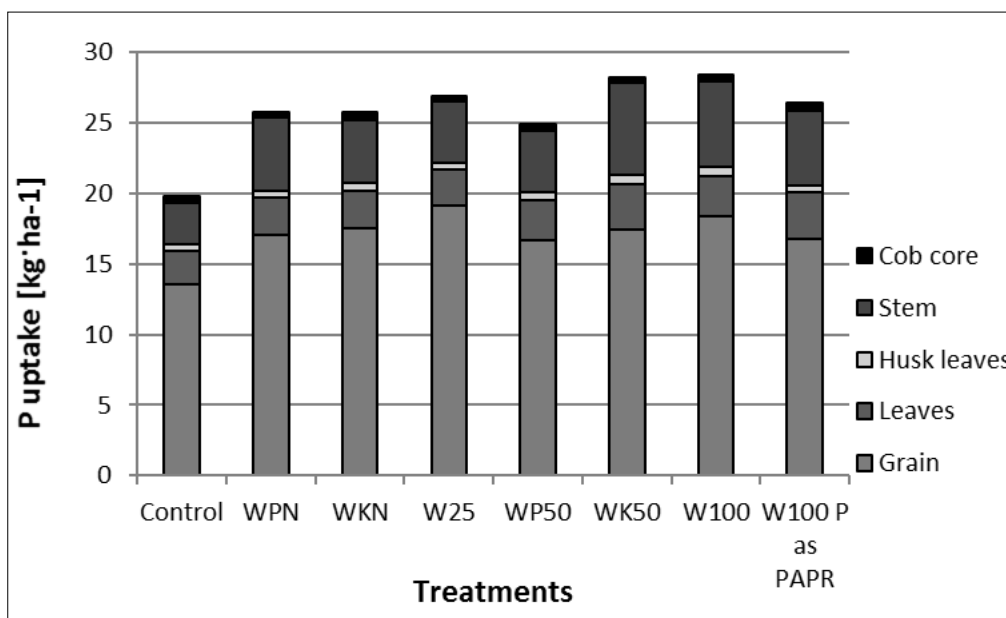

Fig. 2. Structure of phosphorus accumulation in maize at physiological maturity (BBCH 87) (mean 2007–2011)

macher et al. 1994]. High nutrient accumulation in grain indicates strong relationships between plant nutritional status and the amount of harvested yield. Application of PAPR as an alternate P source (W100 PAPR) had no effect on the total P accumulation in maize when compared to the treatment with single superphosphate (W100). Only a decreasing tendency in the total P uptake was observed as a result of PAPR application, which was 7% when compared to W 100 treatment.

In contrast to nitrogen and phosphorus, the majority of potassium was accumulated in maize stems (Fig. 3). Potassium harvest index (KHI) ranged from 20–27%, depending on the treatment (Table 3). The highest K accumulation in grain was observed in the treatment with no potassium fertilizer (WKN) for 10 years. Neglecting P or K fertilization resulted in much lower reduction of nitrogen and phosphorus accumulation in grain than that observed in the case of potassium. When compared to the treatment with the optimal fertilization level (W100), outstanding reduction of potassium uptake (26%) was observed in WKN treatment. The difference between K uptake in the control treatment when compared to that in WKN was 13%. Similar relationships with regard to K accumulation in maize under differentiated NPK fertilization were reported by other authors [Paramasivan et al. 2011].
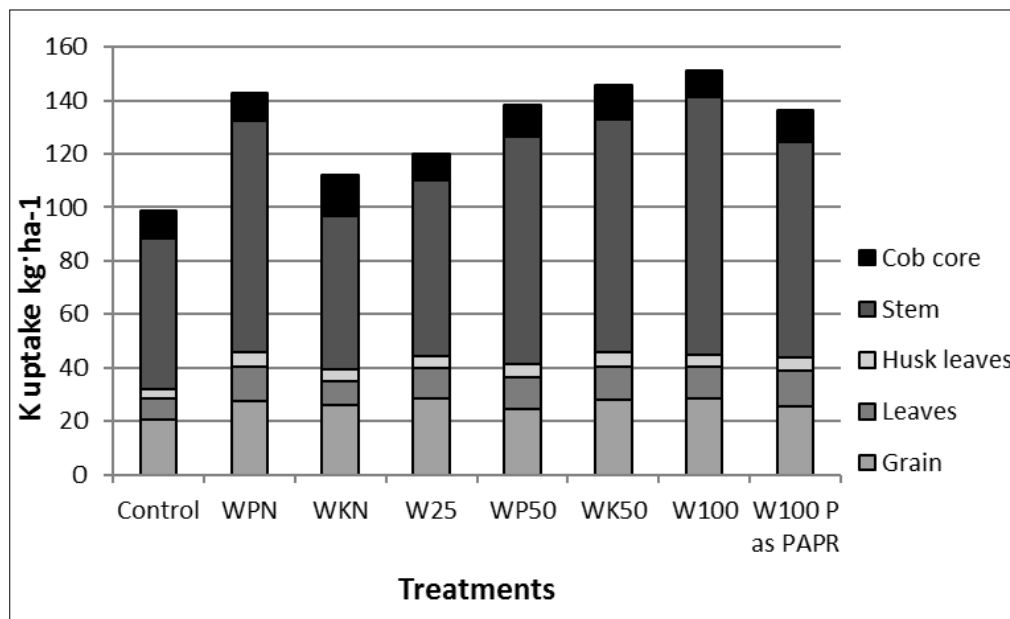

Fig. 3. Structure of potassium accumulation in maize at physiological maturity (BBCH 87) (mean 2007–2011)

Regardless of the treatment applied, regression analysis showed that maize grain yield was determined to the largest extent by the total accumulation of nitrogen (Table 4), exclusive of W100 treatment and the absolute control. In the two latter treatments, there were found significant relationships between yield and the total N, P and K accumulation (W100) as well that of N and K (control).

Stepwise regression analysis including relationship between yield and nutrient accumulation in individual organs (grain, stems, leaves, husks, cob cores) and specific nutrient uptake,

Table 4. Regression models of maize grain yield as the function of nutrient uptake at physiological maturity of maize

Treatments	Regression models	R^2
Control	$y = 0.0222N + 0.0516P + 0.0069K + 1.5476$ (***) (*) (***)	0.934
WPN	$y = 0.0204N + 0.0506P + 0.0058K + 2.2014$ (***) (*)	0.874
WKN	$y = 0.0190N + 0.0303P + 0.0025K + 3.4422$ (***) (**)	0.910
W25	$y = 0.0256N + 0.0101P - 0.0005K + 2.9148$ (***) (***)	0.919
WP50	$y = 0.0279N + 0.0151P - 0.0002K + 2.2946$ (***) (***)	0.950
WK50	$y = 0.0176N + 0.0090P + 0.0112K + 2.8776$ (**)	0.790
W100	$y = 0.0147N + 0.1088P + 0.0076K + 1.2276$ (***) (**) (*)	0.887
W100 P as PAPR	$y = 0.0192N + 0.1676P - 0.0012K + 0.1140$ (***) (**)	0.825

Treatments – explanation as in Table 1
Significat at: 0'***', 0.001'**', 0.01'*'

showed differentiation depending on the treatment. The relationships are presented in table 4. In each of the treatments analyzed, grain yield was determined to the biggest extent by nitrogen accumulation in grain, and then by accumulation of other nutrients examined in the present study. One exception was W25 treatment, which showed the relationship of maize yield only with N accumulation in grain, as described by the presented equation: y (yield) = 0.06UG + 4.99, R^2 = 0,919; where: UG – accumulation N in grain.

The specific rate of nutrient uptake provides information on nutrient amount per unit of harvested yield. The analysis of experimental factor action showed that it significantly differentiated potassium uptake. Significant differences in N uptake were shown only when compared to the control treatment (Table 3). With regard to the specific rate of P uptake, an increasing tendency was observed as a result of mineral fertilization (not including WP50 treatment). The values obtained for the indexes analyzed in the present study were lower in comparison to those reported by other authors [Potarzycki 2010b, Wrońska et al. 2007]. Considerably large differ-

ences were observed in the case of nitrogen. In the present study, the specific rate of nitrogen uptake was on average 21 kg N·t^{-1}, whereas that reported by Potarzycki [2010b] was at a level 30 kg N·t^{-1}. The success of effective production of maize grain relies upon the reduction of plant uptake of nitrogen per yield unit, and this is possible under the conditions of appropriate plant nutrition with other nutrients.

CONCLUSIONS

1. Nitrogen, phosphorus and potassium concentrations in maize organs at the stage of physiological maturity were depended on analyzed organ and were significantly differentiated by the experimental factor.
2. When compared to the control treatment, differentiated P and K fertilization rates significantly increased nitrogen concentration in maize organs (with the exception of stems), on the other hand, they ambiguously affected the differences in P and K concentrations observed between the treatments tested.
3. The form of phosphorus applied as fertilizer had no significant effect on P concentration in maize organs as well as on the total accumulation of phosphorus in the plant.
4. The percentage share of nutrients accumulated in maize grain in the total nutrient accumulation in aboveground biomass showed significant differentiation under P and K fertilization. Nitrogen and phosphorus were accumulated for the most part in maize grain 60–70%), whereas potassium – in maize stems (50–61%).
5. Regardless of the treatment examined, regression analysis showed that maize grain yield was determined to the largest extent by the total accumulation of nitrogen in the plant.

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AKUMULACJA AZOTU, FOSFORU I POTASU PRZEZ KUKURYDZĘ W FAZIE DOJRZAŁOŚCI PEŁNEJ W WARUNKACH ZRÓŻNICOWANEGO NAWOŻENIA MINERALNEGO

Synopsis. W latach 2007–2011 przeprowadzono doświadczenie polowe z kukurydzą, którego celem było określenie wpływu zróżnicowanego nawożenia mineralnego fosforem i potasem na zawartość N, P i K w organach kukurydzy oraz akumulację tych składników w fazie dojrzałości fizjologicznej. Jednoczynnikowy eksperyment założono w układzie bloków losowych kompletnych w czterech powtórzeniach dla każdego obiektu. Przeprowadzone badania wykazały, że czynnik doświadczalny istotnie różnicował zawartość makroskładników w analizowanych organach. W przypadku zawartości azotu nawożenie mineralne P i K istotnie zwiększyło jego zawartość w porównaniu do wariantu kontrolnego. W odniesieniu do zawartości fosforu i potasu stwierdzono istotny wpływ czynnika doświadczalnego na kształtowanie różnic pomiędzy obiektami, ale nie w każdym przypadku zanotowano wzrost zawartości składników w analizowanych organach w porównaniu do obiektu kontrolnego. Szczególnie silna reakcja kukurydzy na brak nawożenia potasem oraz zmienne dawki tego składnika w nawozie uwidoczniła się w łodygach, a także w liściach i koszulkach. Forma fosforu aplikowanego w nawozie nie miała istotnego wpływu na zawartość P w analizowanych organach kukurydzy, a także całkowitą akumulację pierwiastka przez roślinę. Nagromadzenie analizowanych składników w ziarnie względem całkowitej akumulacji pierwiastków w biomasie nadziemnej wykazało istotne zróżnicowanie pod wpływem nawożenia P i K. Azot i fosfor zakumulowane były w większości w ziarnie kukurydzy (60–70%), natomiast potas w łodygach (50–61%). Niezależnie od analizowanego wariantu doświadczalnego analiza regresji wykazała, że plon ziarna kukurydzy w największym stopniu determinowany był przez całkowitą akumulację azotu.

Słowa kluczowe: kukurydza, indeks żniwny akumulacji składników, pobranie składników, dojrzałość fizjologiczna