Effects of different phosphorus and potassium fertilization on contents and uptake of macronutrients (N, P, K, Ca, Mg) in winter wheat

II Uptake of macronutrients

Wpływ zróżnicowanego nawożenia fosforem i potasem na zawartość i pobranie makroskładników przez pszenicę ozimą

II Pobranie makroskładników

Renata GAJ [1*] and Katarzyna RĘBARZ[2]

[1]Department of Agricultural Chemistry and Environmental Biogeochemistry,

Poznań University of Life Science, ul. Wojska Polskiego 71F, 60-625 Poznań, Poland

[2]Department of Agronomy, Poznań University of Life Sciences

*correspondence: grenata@up.poznan.pl

Abstract

The aim of this study was the assessment of macronutrient (N, P, K, Ca, Mg) accumulation in wheat at the critical phases of yield shaping as well as at the full ripening stage when judged at optimal P and K fertilizer rates applied as well as at reduced levels of fertilization with these elements. Four-year-long investigation on winter wheat was carried out in 2007-2010 within an agricultural holding located in vicinity of Śrem city (western Poland). The experiment was conducted under field conditions and based on the randomized-block design with four replications for each treatment. The factors investigated were differentiated P and K rates applied at constant N and Mg levels. Macronutrient accumulation in wheat differed depending on the element studied, plant development stage as well as P and K fertilization levels. The highest differentiation in macronutrient accumulation was observed at wheat flowering stage. At the full ripening stage, there were observed attributable to mineral fertilization significant differences in accumulation of K and Mg. Regression analysis proved that wheat grain yield was determined to the biggest extent by accumulation of K at BBCH 31 stage and that of N at BBCH 92 stage.

Keywords: nutrient harvest index, nutrient uptake, winter wheat

Streszczenie

Celem przeprowadzonych badań była ocena akumulacji makroskładników (N, P, K, Ca, Mg) w pszenicy w fazach krytycznych kształtowania plonu oraz dojrzałości pełnej rozważana w aspekcie dawki optymalnej oraz zredukowanego poziomu nawożenia mineralnego fosforem i potasem. Czteroletnie badania z pszenicą ozimą przeprowadzono w latach 2007-2010 w gospodarstwie rolnym w okolicach Śremu. Doświadczenie polowe założono w układzie bloków losowych w czterech powtórzeniach dla każdej kombinacji. Czynnikiem badanym były zróżnicowane dawki fosforu i potasu, przy stałym poziomie nawożenia azotem i magnezem. Akumulacja makroskładników w pszenicy była zróżnicowana w zależności od pierwiastka, analizowanej fazy rozwojowej roślin oraz poziomu nawożenia mineralnego P i K. Niezależnie od fazy rozwojowej pszenicy, nawożenie mineralne istotnie zwiększyło akumulację wszystkich analizowanych makroskładników w porównaniu do wariantu kontrolnego. Największe zróżnicowanie w akumulacji składników pod wpływem zmiennych dawek P i K odnotowano w fazie kwitnienia pszenicy. W fazie dojrzałości pełnej istotne różnice pod wpływem zróżnicowanego nawożenia mineralnego odnotowano w akumulacji potasu i magnezu. Analiza regresji dowiodła, że plon ziarna pszenicy w największym stopniu determinowany był przez akumulację potasu w fazie BBCH 31 oraz azotu w fazie BBCH 92.

Słowa kluczowe: indeks żniwny akumulacji składników**,** pobranie składników, pszenica ozima

Introduction

Sustainable agriculture requires maximization of the use of macronutrients at synchronized minimization of their losses to the environment (Reijntjes et al. 1992) Nutrient mining is a major cause of low crops and unsustainable agriculture. High crop yields in agricultural plant production strongly rely upon the input of fertilizers that are mostly applied as a mixture of nutrients (FAO 2008). For appropriate determination of plant nutritional needs, there is necessary essential knowledge on the total nutrient requirement, whereas for determination of nutrient rate in a fertilizer it is also important to take into account the fate of nutrients of secondary yield (Grzebisz, 2012). Analyses of the relation between crop production and nutrient availability during the last decade have shown that even in drier parts of the world, nutrients are often the most limiting factor for crop growth (Seligman and van Keulen 1992; Stangel, et al. 1994). The relevant nutrient relations are: fertilizer nutrient application to nutrient uptake and nutrient uptake to crop yield. Not balanced mineral fertilization with K and P is most often the reason of low utilization of nitrogen. Current N management strategies for world cereal production systems have resulted in low efficiency of fertilizer use (Cassman, et al. 2002; Fageria, Baligar, 2005). The relation between nutrient uptake and yield, which reflects the efficiency of nutrient utilization is expressed in economic products, e.g. grains (Duivenbooden, et al. 1994). In order to maximize use efficiency of nutrients from mineral fertilizers, an analysis of nutrient amount applied and its uptake is necessary together with determination of limiting factors for nutrient use. During plant vegetation, an important role is played by the pace of accumulation of a mineral nutrient, since it is crucial for plant growth speed (Grzebisz, 2009). A level of plant yielding is directly connected with the amount of accumulated macro- and microelements in plants (Bergmann, 1992; Czuba, 2000). During the period from the beginning of wheat flowering to full ripening there is shaped 80-90% of grain yield, thus starting just from the latter stage wheat builds previously shaped structure of yield. The aim of the present study was to evaluate the accumulation of macronutrients (N, P, K, Ca and Mg) in wheat at the critical stages of shaping yield as well as the full ripening stage, when judged at optimal P and K rates applied and at reduced levels of fertilization with these elements.

Materials and methods

Characteristics of the experiments carried out are described in the first part of the study. The analysis of nutrient uptake by wheat was performed at 3 timings falling on the beginning of stem elongation (BBCH 31), flowering (BBCH 65) and full ripening (BBCH 92). Nutrient uptake was calculated based on the product of multiplication of plant biomass at a given development stage and respective nutrient content. Analyses of nutrient contents were carried out following standard methods (N - Kjeldahl method, P – calorimetric technique, K and Ca - flame photometry, Mg - atomic absorption spectroscopy). The values of nutrient harvest indexes were calculated based on the ratio of nutrient accumulation in grain to the total nutrient uptake of a given element at the full ripening stage.

Statistical analyses of the results were performed with the use of ANOVA for one-factor experiments.

Results and discussion

N, P, K Ca and Mg uptakes, as calculated by multiplying respective nutrient concentration in crop with the yield (grain and straw) are shown in Figures 1, 2, 3, 4 and 5. Differences in nutrients uptake in the years of observation were mainly due to the differences in the yield obtained. Macronutrient accumulation in wheat was also differentiated depending on the element studied, wheat development stage as well as K and P fertilization levels.
At the stage of stem elongation, ANOVA results showed significant differences in K, Ca and Mg uptake as the effect of the experimental factor. Neither the lack of P fertilization at sufficient N and K supply for plants nor phosphorus fertilizers' rates had any practical effect on P accumulation at BBCH 31 (Figure 2).
Correlation analysis taking into account relation between nutrient accumulation at the critical phase (BBCH 31) and grain yield showed significant relationships for P, K and Mg (Table 1).

Table 1. Correlation coefficients between yield of winter wheat and uptake of nutrients (n=32)

Tabela 1. Współczynniki korelacji między plonem ziarna pszenicy a akumulacją składników w wyznaczonych fazach rozwojowych pszenicy (n= 32)

Timing of nutrient accumulation Terminy akumulacji składników	Uptake of macronutients Pobranie makroskładników				
	N	P	] K	Ca	Mg
BBCH 31	0.344	0.485*	0.477*	-0.046	0.537*
BBCH65	0.184	0.165	0.094	-0.003	-0.061
BBCH 92	0.786*	0.698*	0.839*	0.252	0.568*

correlation significant at $p < 0.05$ korelacja istotna na poziomie p< 0,05

Stepwise regression with backward elimination showed that wheat grain yield was determined to the highest extent by accumulation of K in leaves at BBCH 31 stage which is shown by the following equation:
$Y = 0.029*KBBCH31 + 4.85$ for $R^2 = 0.23$; $p < 0.005$; n =32 (equation 1)

Wheat takes the largest amounts of K during the period of intensive biomass increment, in other words from the beginning of stem elongation to the end of heading. Cereal producers' task is to create appropriate conditions for plants to uptake a nutrient from soil. At the end of vegetative development, K is the nutrient which decides about the pace of transport of assimilates into the ear.
Not sufficient enough K supply at the stage of plant intensive growth results in certain production effects caused by disturbances in building the elements of yield structure. The highest influence of the experimental factor on the differences in uptake of the macronutrients analyzed was indicated at wheat flowering stage. For all the macronutrients analyzed, there were recorded significant increases in nutrient accumulation when compared to the control. Likewise, there were found significant differences among fertilizer treatments. The highest amounts of N and K were accumulated by wheat regardless the year of observation (Figures 1,3).

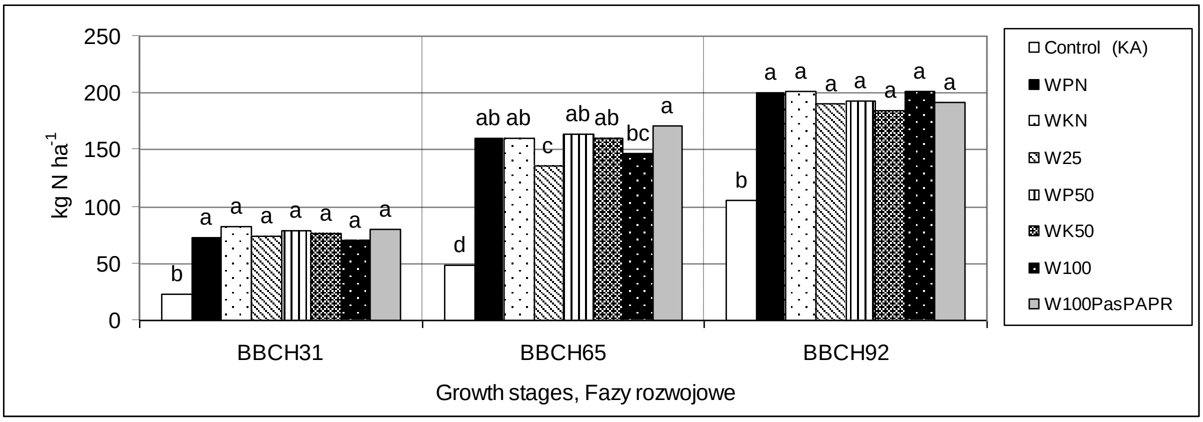

Figure 1. Total nitrogen uptake depending on winter wheat growth stage, (kg*ha^{-1})
Rysunek 1. Całkowite pobranie azotu w zależności od fazy rozwojowej pszenicy ozimej, (kg*ha^{-1})

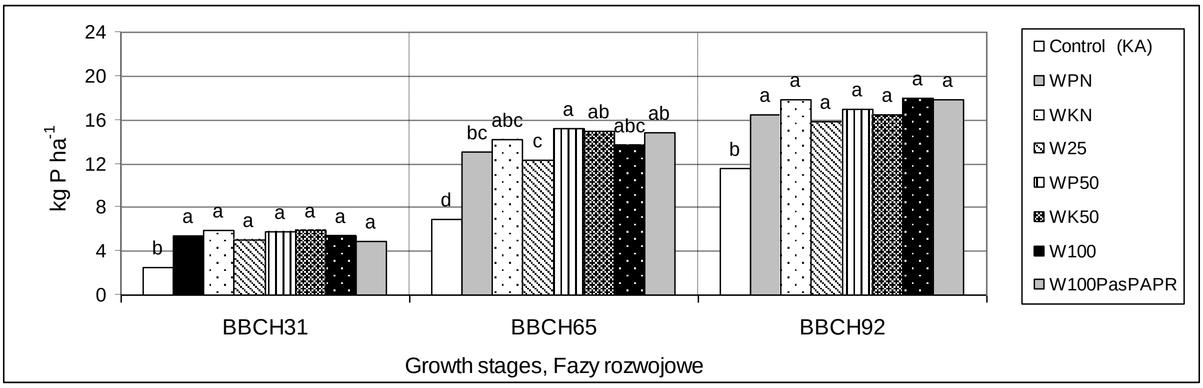

Figure 2. Total phosphorus uptake depending on winter wheat growth stage (kg*ha^{-1})
Rysunek 2. Całkowite pobranie fosforu w zależności od fazy rozwojowej pszenicy ozimej, (kg*ha^{-1})

The lack of K fertilization for 10 years (treatment WKN) resulted in significant reduction of K accumulation in the above-ground biomass produced. At the same time, at the site with no K fertilization, antagonistic interactions between K and Mg as well as K and Ca were indicated most clearly. Antagonistic action of K as regard Mg has been well documented in subject literature (Tage, 1993; Marschner, 1986).

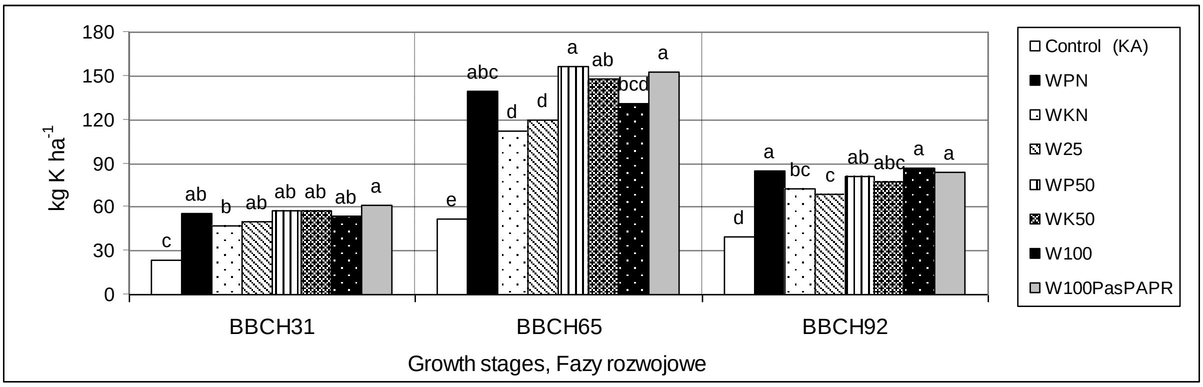

Figure 3. Total potassium uptake depending on winter wheat growth stage (kg*ha^{-1})
Rysunek 3. Całkowite pobranie potasu w zależności od fazy rozwojowej pszenicy ozimej, (kg*ha^{-1})

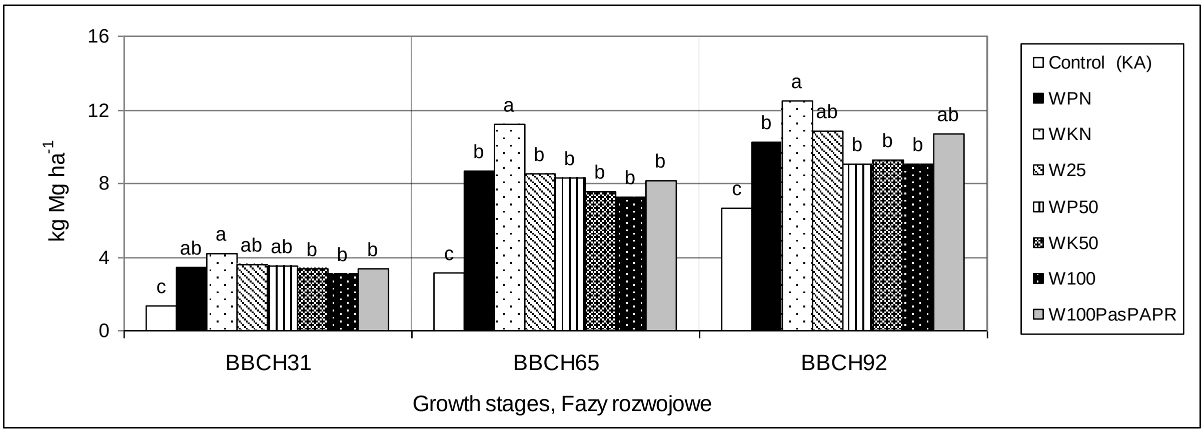

Figure 4. Total magnesium uptake depending on winter wheat growth stage (kg*ha^{-1})
Rysunek 4. Całkowite pobranie magnezu w zależności od fazy rozwojowej pszenicy ozimej, (kg*ha^{-1})

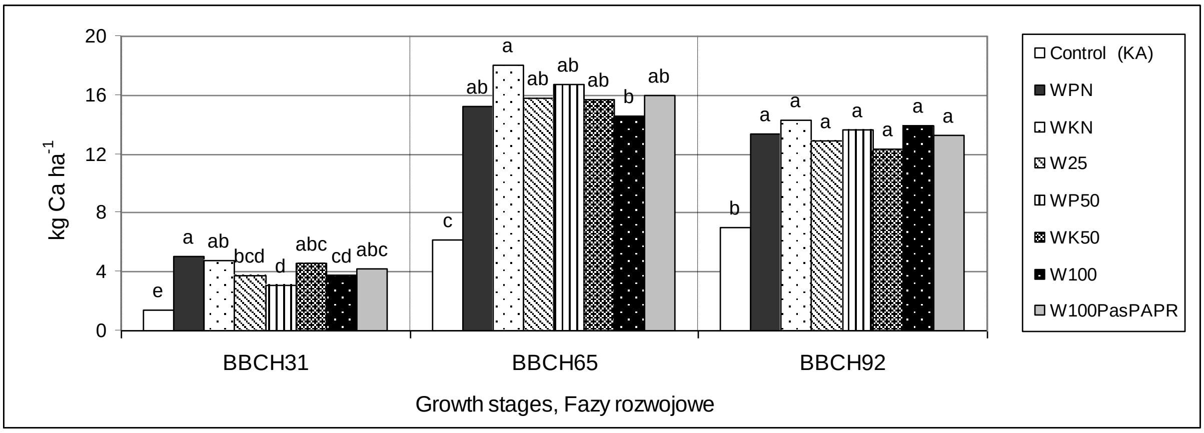

Figure 5. Total calcium uptake depending on winter wheat growth stage (kg*ha^{-1})
Rysunek 5. Całkowite pobranie wapnia w zależności od fazy rozwojowej pszenicy ozimej, (kg*ha^{-1})

As for WKN treatment, there was recorded the status where the lack of K fertilization stimulated Mg and Ca uptake (Figures 4, 5). Magnesium is an important nutrient in cereal cultivation and its uptake occurs during the whole vegetation period. The highest requirement for Mg is shown by cereals during vegetative development (tillering and stem elongation stages) and at the stage of fruit development (early milk stage). The above point out to long-term effects of Mg on plant development.
Regardless experimental factor effects, the biggest differences in nutrient accumulation between the years of investigation were observed for Ca. Such wide range of Ca uptake fluctuations was a result of the effects of changeable environmental conditions which shaped Ca availability in soil, i.e. soil humidity, temperature and the conditions for root growth (White, Broadley 2003).
When comparing P accumulation at wheat development stages, one should note that the effect of the experimental factor was analogous to those of other nutrients and most clearly indicated at wheat flowering stage. Research by Dordas (2009) also showed the highest differentiation in P accumulation in wheat at BBCH 65 stage. In the present study, wheat reacted with a decrease of P accumulation in case of the treatments where P and K rates were reduced to 25% when compared to the optimally balanced treatment (WP100) and that where P fertilization had not been applied for 10 years.
Fransson and Bergkvist (2000) emphasized that the amount of P uptake by plants depended on the balance among many compounds with P and different plant abilities to modify their rhisosphere environment.
At the stage of full ripening (BBCH 92), differentiated P and K fertilizer rates had no significant effect on the total uptake of N, P and Ca, whereas K and Mg accumulation was significantly differentiated (Figures 3, 4). Total N uptake on fertilizer treatments ranged from 184 to 202 kg $N*ha^{-1}$. Considerable amount of N uptake was accumulated in wheat grain. Percentage N share accumulated in grain with reference to N accumulation in plant above-ground biomass is defined in subject literature as N harvest index. In the present study N index values obtained ranged from 69-73% and were significantly differentiated depending on P and K fertilization levels (Table 2). According to Barbottin, et al. (2005); Gebbing and Schnyder (1999); Papakosta and Gagianas (1991), nitrogen included in grain is derived from the reserves accumulated before flowering in vegetative organs, whereas the rest of this nutrient is taken by the plant from soil.
The processes of N flows between older and younger plant organs are basic growth factors, and consequently they determine yield. N deficiency at the stage of grain ripening (milk stage) shortens the period of wheat maturing (Tahir and Nakata, 2005). When taking the production criterion, the high value of N harvest index points out to appropriate management of the grain-field. High accumulation of N is also a sign of environmental safeguarding, since it indicates potentially lower amounts of nitrate N in soil, and these easily leach after plant harvesting.
According to literature data the range of nutrient harvest index values is broad (60-85%) and index values change depending on cereal species, weather conditions and agricultural factors, including fertilization with nitrogen (Grzebisz, 2009). Nutrient harvest index is prone not only to N rate, but also other nutrients such as Ca, P and K which was confirmed by the results of the present study (Table 2). Nitrogen accumulation should be viewed from the perspective of K accumulation, which achieves the maximum during the period from tillering to the beginning of flowering. At wheat flowering, K accumulation on fertilizer treatments was in a range from 112 kg K (WKN treatment) to 153 kg K (WP50 treatment). In the period from the

beginning of stem elongation to the stage of flowering, K uptake increased almost three-fold (Figure 3). At wheat flowering, K accumulation at the fertilizer treatments was higher when compared to that at the stage of full ripening, and depending on the treatment it ranged from 69 to 86 kg K*ha^{-1}.

Table 2. Nutrient harvest indexes according as differentiated P and K fertilization
Tabela 2 Indeksy żniwne makroskładników na tle zróżnicowanego nawożenia P i K

Treatments Obiekty	Indexes Indeksy,				
	N	P	K	Mg	Ca
Control Kontrola , (KA)	72.8^{a}	79.3^{ab}	44.7^{a}	74.9^{abc}	21.21^{a}
WPN	71.1^{ab}	82.8^{abc}	36.5^{c}	76.8^{a}	17.6^{bc}
WKN	70.6^{ab}	81.5^{bcd}	43.8^{a}	73.5^{abc}	16.5^{bc}
W25	69.4^{b}	82.8^{ab}	41.5^{ab}	71.4^{bc}	15.8^{bc}
WP50	70.7^{ab}	85.3^{a}	35.4^{c}	71.3^{c}	18.8^{ab}
WK50	71.3^{ab}	79.2^{cd}	34.0^{c}	76.4^{ab}	14.74^{c}
W100	69.2^{b}	79.1^{d}	34.7^{c}	75.1^{abc}	15.6^{c}
RBF-PAPR (P as PAPR) (P jako – PAPR)	70.9^{ab}	82.6^{abcd}	36.9^{bc}	72.4^{abc}	15.7^{c}
Interaction Year×Treatments Interakcja Rok×Obiekt	s	s	s	s	s

Means indicated by different letters are significantly different (Tukey's Test, p<0.05), s - factor affected significantly by years
Średnie oznaczone różnymi literami różnią się od siebie istotnie (test Tukeya dla p < 0,05);
s- lata wpłynęły istotnie na czynnik

Phosphorus acquirement in the plant goes in a different way than that in case of N and K accumulation processes, since P uptake starts increasing from vegetation beginning in the spring until the flowering stage and then it stabilizes. Starting from flowering as far as grain shaping, there reveals the second critical phase of P requirement in plants. In this period the nutrient becomes indispensable for maintaining rapidity of biochemical and physiological processes, such as remobilization of nitrogen and accumulation of auxiliary P forms in grains (Grzebisz 2012). Furthermore, P uptake after flowering suggests post-anthesis root growth, as root hairs must expand towards P resources in order to take up the nutrient (Clark 1990). The factor which strongly differentiated P accumulation in wheat plants was the course of weather during the years of observation. Total average uptake of P with grain and straw yield was 17 kg P·ha^{-1} being strongly differentiated in observation years. During the whole experiment, accumulation of P in wheat was decreasing in years as follows 2007>2008>2010>>2009. In any case, significant differentiation of P uptake was reflected in the contrast between fertilizer treatments and the absolute control (no fertilizer at all). Disparate to the results of other researchers (Aulakh, et al. 2003; Feiza, et al. 2003; Moskal, et al. 1999), in the present study there were not observed significant differences between P total uptake on phosphorus treated objects and those untreated. Accumulation of this nutrient in cereals is determined mainly by its movement from the stem to the ear, the process of which starts before plant flowering (Manske, et al. 2001). Research by Khan, et al. (1986) and Ishaq, et al. (2001) showed that a way of soil cultivation is an important factor which determines P uptake, which is directly associated with root system development, and consequently with water and nutrient uptake. The structure of plant root system plays a particularly important role in P uptake in view of the fact that the nutrient shows low mobility in soil (Kirkby and Römheld 2006). Achieving high P fertilization efficacy is linked not only with phosphate uptake from soil, but it also depends on translocation of the nutrient amid plant organs (Sattelmacher, et al. 1994). In the present study, wheat did not indicate yield increase due to growing rates of P applied, however this does not mean that plant nutritional demand for this nutrient was low. This plant species can show differentiated demands for P depending on the variety and utilization direction and the differences observed are resultant of protein metabolism. The demands of quality wheat cultivars with regard to phosphorous are considerably higher than those of bread cultivars. In this study, the bread variety Kris with grain yield more than 7 $t \cdot ha^{-1}$ needed 2.4 kg P for the production of yield unit. On the other hand, in case of quality wheat, Gaj (2008) showed the optimal range of P uptake which was from 2.9 to 3. 2 kg $P \cdot t^{-1}$. According to literature data, wheat accumulates about 90% of P in grain. In the present study, average P harvest index was 80%. There has to be taken into account the fact that high accumulation of phosphorus in grain comes to unconditional loss of this nutrient from a given field. This aspect should be particularly regarded in agricultural holdings oriented exclusively towards plant production (Grzebisz, 2012). The ratios of P accumulation in grain and P total uptake can range from 30 to 90%, depending on the variety and growth conditions (Batten and Khan 1987). In this study, wheat did not indicate significant differences in P uptake when fertilized with different P forms. The lack of wheat response to the form of P fertilizer points out to comparable effects of single super phosphate fertilizer and partially acidulated phosphate rock (PAPR) as phosphorus carriers. This means that in view of possibilities of P uptake by wheat, the effects of both fertilizers are the same. The lack of response of other species of cultivated plants to different forms of P applied was also observed by other authors Gaj (2008, 2012). Grzebisz and Potarzycki (2003) showed that under the conditions of acidic soils, P from reactive phosphorites can act alike P from superphosphate. In this study, differentiated fertilizer rates of P and K had no significant effects on the total uptake of N and Ca at the full ripening stage, whereas they significantly differentiated accumulation of K and Mg (Figures 3,4). Regression analysis proved that grain yield (GY) was determined to the biggest extent at BBCH 92 stage as it is presented by the equation below:

$GY92 = 0,019*upN92t + 2.75$ dla $R2 = 0.63$; $p < 0.000$; $n = 32$
(equation 2)

Numerous studies have already showed, that plant biomass produced under certain environmental conditions is a function of nitrogen uptake into the plant (Gastal and Lemaire, 2002; Lawlor ands Cornic 2002).

Conclusions

1. The effect of differentiated mineral fertilization with P and K on accumulation of all the nutrients analyzed was most unambiguous at wheat flowering stage.
2. At the full ripening stage, differentiated P and K fertilizer rates had no effect on the total uptake of N, P and Ca but they significantly differentiated. accumulation of K and Mg.
3. Regression analysis showed, that wheat grain yield was determined to the biggest extent by K accumulation in wheat leaves at BBCH 31 stage and total accumulation of N at full ripening stage BBCH 92.
4. The form of P applied as fertilizer had no significant effects on accumulation of this nutrient at all wheat development stages analyzed.
5. Differentiated mineral fertilization significantly influenced nutrient harvest indexes; 70-80% of N, P and Mg were accumulated in grain, whereas Ca and K – in straw.

References

Aulakh, M.S., Kabba, B.S., Baddesha, H.S.,Bahl, G.S., Gill, M.P.S. (2003) Crops yields and phosphorus fertilizer transformations after 25 years of applications to a subtropical soil under groundnut-based cropping systems. Field Crops Research, 83, 283-296.

Barottin, A.C., Lecomte, C., Bouchard C., Jeuffroy M.H. (2005) Nitrogen remobilization during grain filling in wheat: genotypic and environment effects. Crop Science, 45, 1141-1150.

Batten, G.D., Khan M..A. (1987) Effect of time of sowing on grain and nutrient uptake of wheat with contrasting phenology. Australian Journal Agriculture Research, 27, 884-887.

Bergmann, W. (1992) Nutritional Disorders of Plants, Development, Visual and Analytical Diagnosis. Gustaw Fisher Verlag Jena, Stuttgart, New York.

Cassman, K.G., Dobermann, A., Walters, D.T. (2002) Agroecosytems, nitrogen use-efficiancy, and nitrogen management. Ambio 31, 132-140.

Clark R.B. (1990) Physiology of cereals for mineral nutrient uptake use and efficiency. In: Baligar V.C. and Dunkan R.R (eds): Crops as enhancers of nutrient use, London, Academic Press, 131-210.

Czuba, R. (2000) Mikroelementy we współczesnych systemach nawożenia. Zeszyty Problemowe Postępu Nauk Rolniczych, 471, 161-170.

DeMarco, D.G. (1990) Early growth of wheat seedlings as affected by seed weight, seed and nitrogen. Australian Journal of Agriculture, 30, 545-547.

Dordas, Ch. (2009) Dry matter, nitrogen and phosphorus accumulation, partitioning and remobilization as affected by N and P fertilization and source-sink relations. European Journal of Agronomy, 30, 129-139.

Duivenbooden, N.V. Wit, C.T.D., Keulen, H.V. (1996) Nitrogen, phosphorus and potassium relation in five major cereals reviewed in respect to fertilizer recommendations using simultation modeling. Fertilizer Research 44: 37-49.

Fageria, N.K., Baligar, V.C. (2005) Enhancing nitrogen use efficiency in crop plants. Advance Agronomy, 88, 97-185.

Feiza, V., Feiziene, D., Riley H.C.F. (2003) Soil available P and P offtake responses to different tilagge and fertilisation systems in the hilly moranic landscape of western Lithuania. Soil&Tilage Research, 74, 3-14.

Food Agricultural Organization (2008) Current World Fertilizer Trends and Outlook to 2011/12. FAO, Rome, Italy.

Fransson A., Bergkvist B. (2000) Phosphorus fertilization causes durable enhancement of phosphorus concentrations in forest soil. Forest Ekology and Management, 130, 69-76.

Gaj, R. (2008) Sustainable management of phosphorus in soil and plants in condition of intensive plant production. Nawozy i Nawożenie, Fertilizers and Fertilization, Z.33.

Gaj, R. (2012) The effect of different phosphorus and potassium fertilization on plant nutrition in critical stage and yield of winter triticale. Journal of European Central Agriculture. V13(4), 704-716.

Gastal, F., Lemaire, G. (2002) N uptake and distribution in crops: an agronomical and ecophysiological perspective. Journal of Experimental Botany 53 (370), 789-799.

Gebbing, T., Schnyder, H. (1999) Pre-anthesis reserve utilization for protein and carbohydrate in grains of wheat. Plant Physiol.121: 871-878.

Grzebisz, W. (2009) Nawożenie roślin uprawnych. Cz.2: Nawozy i nawożenie. PWRiL, Poznań.

Grzebisz, W. (2012) Technologie nawożenia roślin uprawnych – fizjologia plonowania. T.2. Zboża i kukurydza. PWRiL, Poznań.

Grzebisz, W., Potarzycki, J. (2003) Czynniki kontrolujące pobieranie fosforu przez rośliny. Pierwiastki w środowisku (ed. Grzebisz W.).Journal of Elementology, V.8(3): 33-46.

Ishaq, M., Ibrahim, M., Lal, R. (2001) Tillage effect on nutrient uptake by wheat and cotton as influenced by fertilizer rate. Soil&Tillage Research, 62, 41-53.

Khan, B.R., Khan B., Razzaq A., Munir M., Aslam M., Hobbs P.R. (1986) Effect of different tillage implements on the yield of wheat. Pak. Journal Agriculture Research, 7, 141-147.

Kirkby, E., Römheld, V. (2006) Physiological aspects of plant phosphorus in relation to its acauisition from the soil by crop plants. The International Fertiliser Society, Proceedings 588.

Lawlor, D.W., Cornic, G. (2002) Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. Plant, Cell & Environment, (V 25), 275-294.

Manske, G., Ortiz-Monasterio, J.I., Ginkel, M., Gonzalez, R.M., Fischer, R.A., Rajaram, S., Vlek, P.L.G. (2001) Importance of P uptake efficiency versus P utilization for wheat yield in acid and calcareous soils in Mexico. European Journal of Agronomy, 14, 261-274.

Marschner, H. (1986) Mineral nutrition of higer plants. Academic Press inc. London.

Moskal, S., Mercik, S., Turemka, E., Stępień, W. (1999) Bilans fosforu nawozowego w wieloletnich doświadczeniach polowych w Skierniewicach. Zeszyty Problemowe Postępów Nauk Rolniczych, 465, 61-69.

Papakosta, D., Gagianas, A. (1991) Nitrogen accumulation, remobilization and losses for meditarranean wheat during grain filling. Agronomy Journal, 83, 864-870.

Reijntjes, C., Haverkort, B., Waters, Bayer, A. (1992) Farming for the future: an introduction to low-external-input and sustainable agriculture. 272 pp

Sattelmacher, B, Horst, WJ, Becker, H.C. (1994) Factors that contribute to genetic variation for nutrient efficiency of crop plants. Z. Pflanzenernähr. Bodenkd., 157, 215-224.

Seligman, N.G., van Keulen, H. (1992) Herbage production of a mediterranean grassland in relation to soil depth, rainfall and nitrogen nutrition: a simulation study. Ecological Modeling, 47, 303-311.

Stangel, P., Pieri, C., Mokwunye, U. (1994) Maintaining nutrient status of soils: macronutrients. In: Greenland, D.J., Szaboles, I. (eds): Soil resilience and sustainable land use, 171-197 pp, Wellingford: CAB Intern.

Tage, J.S. (1993) Interaction between Plant Nutrients: III. Antagonism between Potassium, Magnesium and Ca. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science, V 43(1),1-5.

Tahir, I.S.A., Nakata, N. (2005) Remobilization of nitrogen and carbohydrate from stems of bread wheat in response to heat stress during grain filling. Journal Agronomy Crop Science 191(2), 106-115.

White, P.J., Broadley M.R. (2003) Calcium in plants. Ann Botany, 92, 487-511.