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

I. Content of macronutrients

Wpływ zróżnicowanego nawożenia fosforem i potasem na zawartość i pobranie makroskładników (N, P, K, Mg, Ca) przez pszenicę ozimą

I Zawartość makroskładników

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Abstract

The aim of the study carried out under field conditions was to evaluate the effect of differentiated phosphorus and potassium fertilization level on nutritional status of winter wheat at stem elongation (BBCH 31) and flowering (BBCH 65) development stages as well as on macronutrient contents in yield obtained (grain and straw). The research was conducted in 2007-2010, within an individual agricultural holding, on lessive soil with medium and high richness in potassium and phosphorus, respectively. The contents of nitrogen, phosphorus, potassium, magnesium and calcium in wheat changed depending on the organ assessed and plant development stage. At BBCH 31, regardless fertilization level, the plants observed were malnourished with potassium, phosphorus and calcium and at the control site – also with nitrogen. Furthermore, there were found significant correlation relationships among the contents of nutrient pairs: nitrogen-potassium, nitrogen-phosphorus, nitrogen-magnesium and nitrogen-calcium. The content of nitrogen in wheat grain and straw differed mainly due to weather conditions during the study. Irrespective of the years of observation, differentiated rates of P and K applied had no significant effect on N accumulation in wheat at full ripening stage. In contrast to nitrogen, the level of P and K fertilization significantly differentiated the contents of phosphorus, potassium and magnesium in wheat grain and straw. In case of calcium, the effect of fertilization factor was indicated only as regards the content of this nutrient in grain.

Keywords: content of macronutrients, nutritional status, potassium and phosphorus rate, winter wheat

Streszczenie

Celem przeprowadzonych badań polowych było określenie wpływu zróżnicowanego poziomu nawożenia fosforem i potasem na stanu odżywienia pszenicy ozimej w fazie początku strzelania w źdźbło (BBCH31) i kwitnienia (BBCH65) oraz zawartość makroskładników w ziarnie i w słomie pszenicy ozimej. Doświadczenie przeprowadzono w latach 2007-2010 w indywidualnym gospodarstwie rolnym, na glebie płowej o średniej zasobności w potas i wysokiej w fosfor. Zawartości azotu, fosforu, potasu, magnezu i wapnia w pszenicy zmieniały się w zależności od organu rośliny oraz fazy rozwojowej. Niezależnie od poziomu nawożenia mineralnego w fazie BBCH 31 rośliny były niedożywione potasem, fosforem, wapniem, a w stanowisku kontrolnym dodatkowo azotem. Ponadto stwierdzono istotne zależności korelacyjne pomiędzy zawartościami analizowanych par składników: azot - potas, azot – fosfor, azot - magnez oraz azot – wapń. Zawartość azotu w ziarnie i w słomie pszenicy ozimej była zróżnicowana głównie warunkami pogodowymi w latach badań. Zróżnicowane dawki P i K niezależnie od roku badań nie miały również istotnego wpływu na akumulację N w fazie dojrzałości pełnej. W odróżnieniu od azotu, poziom nawożenia mineralnego P i K istotnie różnicował zawartość fosforu, potasu i magnezu w ziarnie i słomie pszenicy. W przypadku zawartości wapnia działanie czynnika nawozowego zaznaczyło się tylko w odniesieniu do zawartości składnika w ziarnie.

Słowa kluczowe: zawartość makroskładników, stan odżywienia, dawki fosforu i potasu, pszenica ozima

Streszczenie szczegółowe

Jednym z podstawowych czynników ograniczających potencjał plonowania pszenicy ozimej jest stan odżywienia roślin w fazach krytycznych. Mając na uwadze potrzeby pokarmowe pszenicy oraz sposób gospodarowania nastawiony na intensywną produkcję, uproszczone zmianowanie, wysoki poziom plonów oraz maksymalne wykorzystanie składników z nawozów należy się zastanowić jak gospodarować składnikami mineralnymi, aby osiągnąć założony plon. Celem przeprowadzonych badań polowych było określenie wpływu zróżnicowanego poziomu nawożenia mineralnego fosforem i potasem na stan odżywienia pszenicy ozimej w fazie początku strzelania w źdźbło (BBCH31) i kwitnienia (BBCH65) oraz zawartość makroskładników w ziarnie i w słomie pszenicy ozimej. Podstawą badań było jednoczynnikowe doświadczenie z pszenicą ozimą odmiany Kris, należącej do grupy odmian chlebowych, klasy B. Doświadczenie stanowiło kontynuację eksperymentu wieloletniego założonego w 2000 roku. Czynnikiem doświadczalnym był zróżnicowany poziom nawożenia mineralnego fosforem i potasem. Eksperyment przeprowadzono na glebie płowej wykształconej z piasków gliniastych, płytko zalegających na glinie zwałowej klasy bonitacyjnej IIIb, o wysokiej zasobności w fosfor (92 mg $P \cdot kg^{-1}$), średniej do niskiej w potas (120- 80 mg $K \cdot kg^{-1}$) oraz średniej w magnez (37 mg $Mg \cdot kg^{-1}$ gleby). Gleba charakteryzowała się odczynem lekko kwaśnym (pH 5,94 1M KCl). Zastosowane warianty nawożenia mineralnego pszenicy ozimej w sposób niejednoznaczny różnicowały zawartość makroskładników w analizowanych organach w zależności od terminu pobierania roślin. Zawartości azotu, fosforu, potasu, magnezu i wapnia w pszenicy zmieniały się w zależności od organu rośliny oraz fazy rozwojowej. W fazie strzelania w źdźbło ocena stanu odżywienia pszenicy makroskładnikami wykazała, że niezależnie od obiektu rośliny były niedożywione potasem, fosforem, wapniem, a w stanowisku kontrolnym dodatkowo azotem. Analiza regresji uwzględniająca zależność plonu ziarna od stanu odżywienia w fazie BBCH 31 wykazała istotną zależność tylko w przypadku magnezu. Poziom nawożenia mineralnego P i K niezależnie od dawki aplikowanych składników i roku badań nie miał istotnego wpływu na kształtowanie różnic zawartości azotu w ziarnie i w słomie pszenicy. Zawartość fosforu, potasu, wapnia i magnezu w ziarnie oraz fosforu i wapnia w słomie w fazie dojrzałości pełnej determinowana była głównie warunkami pogodowymi w latach badań. W ziarnie istotne znaczenie mają nie tylko zawartości poszczególnych składników, ale przede wszystkim prawidłowe proporcje pomiędzy składnikami, które mają kluczowe znaczenie dla oceny wartości konsumpcyjnej i paszowej ziarna. Poziom nawożenia mineralnego fosforem i potasem nie miał istotnego wpływu na stosunek N:P i N:K w ziarnie, natomiast istotnie różnicował następujące relacje pomiędzy składnikami: N:Mg, N:Ca i K:Mg.

Introduction

The use of plant yield-forming potential depends not so much on the amount of nutrients applied to soil as mineral fertilizers but on crop rotation, as well as physical and chemical conditions that affect uptake of mineral elements by plants. Both deficit and excess of macro- and micronutrients in grain for consumption can induce unfavorable changes in animal metabolism (Whitaker, et al., 1997). The concentration of nutrients changes relative to one another in soil and plant through growth (Zhang, et al., 2007). In subject literature there is available only scarce data on the critical contents of nutrients in soil providing for information on phosphorus and potassium fertilization requirements towards assuring maximum yields with good quality. Research results have shown that 50-80% of P applied as fertilizer is adsorbed by soil, however, the amount of P needed to achieve maintenance of its adequate status in soil has not so far been known (Vogeler, et al., 2009). In Poland, specially alarming is the fact that there has been constantly decreasing the use of potassium fertilizers, and this can soon become a significant factor with limiting effects on yield stability. Average content of available K in soil is not sufficient to cover nutritional needs of sensitive and high-yield plants. Intensive crop production in combination with unbalanced fertilization has already resulted in depletion of soil K across large areas of Poland (Igras and Kopiński 2009). Deficiency of K in crop production usually appears as a result of increasing N and P fertilizer applications and neglecting K fertilization (Ju, et al., 2005). Potassium deficiency is a worldwide problem (Dobermann, et al., 1998), and K status in agricultural soils has been declining across the globe - in Europe, Africa, Asia, and North America (Tan, et al., 2012). Nutrient recommendations should not be based only on yield response of single crops, but also on after-effects pertaining to nutrient availability for succeeding crops (Dai et al. 2010). The correct system of P and K fertilization is based on regulation of nutrient availability in soil in the crop-rotation arrangement taken as a whole. Approval of such strategy is also very beneficial with regard to economic aspects since this allows spreading fertilization costs over several years. Plants show considerable need differentiation with reference to P and K fertilization, which is a result of their biology, quantity of biomass produced and the structure of their root system. Optimizing nutrition of cereals is essential to maintain high yield and production quality. Taking into account nutritional needs of wheat as well as management methods oriented towards intensive production, simplified crop rotation, high yield levels and maximum utilization of fertilizer nutrients, there should be attention drawn to the question on how nutrients should be handled to achieve intended yields. In the present study, it was presumed that differentiated pre-sowing P and K fertilization or else its lack had no effect on nutrient contents in plants. The above hypothesis was verified during the investigation carried out, which of the main aim was to assess macronutrient (N, P, K, Ca, Mg) contents at the critical phases of wheat yield shaping as well as on their accumulation in straw and grain yields, when judged at optimal P and K rates applied and at reduced levels of fertilization with these elements.

Materials and methods

The study was carried out in the years 2007-2010 within the Wieszczyczyna agricultural holding in vicinity of Śrem city, Poland, 52º02' N 17º05'E. The research was based on one-factor experiment on winter wheat, variety Kris. Investigated wheat belongs to the group of class B bread wheat varieties. The trial conducted was a part of the long-term experiment which was established in the year 2000. Investigations were carried out based on the randomized-block design with four replications. Differentiated mineral fertilization with phosphorus and potassium was the experimental factor. The observations were carried out on lessive soil, formed on loam and shallow-lying on glacial till. The soil used in the study was of the quality class IIIb and indicated high content of available phosphorus (92 mg P*kg^{-1} of soil). At the same time, the content of available potassium ranged from medium to low (120-80 mg K*kg^{-1}) and that of magnesium was medium (37 mg Mg*kg^{-1}). Soil reaction was slightly acidic (pH 5.94 1M KCl). Every year winter wheat was cultivated after maize. All cultivation practices were carried out according to optimal for wheat agrotechnical demands. Taking into account soil fertility, unit uptake and the expected crop of 7 t·ha^{-1} for the duration of the study, there was determined the optimal mineral fertilization level (W100). Every experimental year, phosphorus rates for treatment W100 were 35 kg P*ha^{-1}, and those of potassium were 100 kg K*ha^{-1} K, except for the year 2007 when K fertilization level was higher and amounted to 133 kg K*ha^{-1}. Determination of the optimal rate (W100) was performed with the use of NawSald software (IUNG, Puławy, Poland). Based on phosphorus and potassium fertilization levels which were balanced with regard to nitrogen, other investigated P and K rates were determined by respective reduction of P and K fertilization down to 25% (W25) and 50% (W50) of the optimally balanced treatment (W100). Additionally, there were established control variants WKN and WPN, where phosphorus or potassium were not applied, respectively, and constant levels of nitrogen and magnesium were maintained. Experimental treatments are described in Table 1.
In accordance with the experiment design, fertilization with phosphorus, potassium and magnesium was carried out at the same rate after harvesting pre-crop plants. Potassium was applied as potassium chloride salt (60% K_2O), phosphorus as single superphosphate, and magnesium as kieserite (27% MgO). In case of WP1 treatment phosphorus was applied as Partially Acidulated Phosphate Rock. The object WP100 was treated as the alternative for single superphosphate as the source of phosphorus. In the study, there was also used rock phosphate with P overall content 10.2% P and acidification 50% (i.e. the amount of sulphuric acid utilized during the technological process on obtaining the product was 50% of the amount necessary for the production of single superphosphate).
Fertilization with nitrogen as ammonium nitrate at a rate 180 kg N*ha^{-1} was carried out during 4 timings (I) 30 kg (kg N*ha^{-1}) – before autumn sowing; (II) 60 kg N*ha^{-1} before the start of spring vegetation; (III) 30 kg N*ha^{-1} – 3 weeks before application of the second N dose (IV) 30 kg N*ha^{-1} – the beginning of earing stage.
At the beginning of stem elongation stage (BBCH-31), the plants for chemical analyses were collected from all experimental plots (from 1 m long spots). Plants collected with a harvester from the area of 20 m^2 were used for assessments of grain yield.

Table 1. Field experimental design

Tabela 1. Schemat doświadczenia polowego

Treatments Obiekty	Description Wyjaśnienie
Control (KA Kontrola)	No fertilizer application during observation years
WPN	No phosphorus fertilization; optimal fertilization with other nutrients (nitrogen, potassium, magnesium)
WKN	No potassium fertilization; optimal fertilization with other nutrients (nitrogen, potassium, magnesium)
W25	25% of PK recommended rate as compared to optimally fertilized treatment; optimal fertilization with N and Mg
WP50	50% of P recommended rate as compared to optimally fertilized treatment; the rest of nutrients applied at optimal rate
WK50	50% of K recommended rate as compared to optimally fertilized treatment; the rest of nutrients applied at optimal rate
W100	100% of P and K recommended rate; treatment optimally balanced with regard to nitrogen and magnesium
W100 (P as PAPR) (P jako – PAPR)	100% of P, K and Mb recommended rate; phosphorus applied as partially acidulated phosphate rock (PAPR)

The plant material was appropriately prepared for determination of nutrient contents. 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). Weather conditions were different during the experimental period (Table. 2).

In all the observation years, there were recorded irregular participation patterns in the months falling on the stages of intensive wheat growth (April, May, June). Most beneficial weather conditions for wheat growth were observed in 2008. The results obtained were statistically analyzed with one-factor ANOVA. The years of treatments were regarded as the random factor and PK fertilization level was the fixed factor. Multiple regression analysis with choice of the best subset of variables was applied for evaluation of cause and effect relationships between the parameters analyzed. The statistical analyses were performed with the use of Statistica© 10 software.

Table 2. Weather conditions during vegetation of winter wheat

Tabela 2. Warunki meteorologiczne w sezonie wegetacyjnym uprawy pszenicy ozimej

Vegetation season Sezon wegetacyjny	Months. Miesiące											
	VIII Aug	IX Sept	X Oct	XI Nov	XII Dec	I Jan	II Feb	III Mar	IV Apr	V May	VI Jun	VII Jul

Temperature (ºC) Temperatura (ºC)												
2006/2007	18.1	17.1	11.1	6.6	4.5	4.6	0.9	6.1	10.1	15.2	19.2	18.7
2007/2008	18.7	13.1	7.9	2.6	1.1	2.0	4.0	4.1	8.5	14.2	18.7	19.8
2008/2009	18.6	13.1	9.0	5.5	1.1	-3.3	-0.3	3.8	11.1	13.4	15.9	19.6
2009/2010	19.1	14.7	7.3	6.2	-1.0	-7.0	-1.7	3.6	8.9	12.3	17.6	21.9
Long-term period Wielolecie	17	13.1	8.3	3.2	0.4	-1.2	-0.4	3.2	7.8	13.6	16.6	18.3
Precipitation (mm) , Opady (mm)												
2006/2007	148	23	35	47	42	86	49	50	6	78	66	112
2007/2008	48	23	15	34	26	65	41	44	5	42	48	126
2008/2009	48	23	15	34	26	72	23	34	38	17	12	46
2009/2010	62	16	61	18	20	25	49	56	19	69	101	86
Long-term period Wielolecie	64	45	40	42	36	30	39	36	51	62	74	64

Results and discussion

Mineral fertilizer treatments applied to winter wheat ambiguously differentiated macronutrient contents in the plant parts analyzed and relied upon the timing of sample collection. The contents of nitrogen (N), phosphorus (P), magnesium (Mg) and calcium (Ca) in wheat changed depending on the plant organ and the development stage. Evaluation of macronutrient nutrition status at the beginning of stem elongation stage (BBCH31) showed that regardless the treatment, plants indicated undernourishment as for K, P and Ca, and additionally as for N when they grew on the control plot (Table 3). Such nutrition status was a sign of sufficient availability of N for plants, both from soil and mineral fertilizers. In case of P, optimal nutritional status was observed only in the experimental variant where fertilization with K was excluded (WKN), whereas on the rest of treatments the content of this nutrient stayed at a level below lower normalized threshold (3-5g•kg^{-1}) determined by Bergmann (1992). Differentiated P rates had no significant effect on shaping differences in macronutrient content among the treatments. This means that in the case of soils rich in available P there is a strong need to verify fertilizer rates as P provision for plants relies upon other factors, such as weather course during the vegetation season, plant growth environment and agriculture techniques applied. Even if soil is rich in available P, its uptake dynamics are considerably lessen under water deficiency conditions. Literature data indicate that water potential effect on P uptake is stronger than that of the content of this element in soil. The transport of P from soil into the plant depends on the diffusion coefficient which is determined by temperature, humidity and soil buffer capacity (Barber 1995, Jungk, Claassen 1997). The movement of P towards plant roots is impeded as soil humidity reduces. Significant differences in leaf P contents during the observation years with differentiated precipitation distribution during vegetation seasons (Table 2) confirm the above findings. In this study, there were found analogous P contents in the leaves of wheat at the critical growth stage to those reported by other authors (Haneklaus and Schnug 1998).

Table 3. Content of nutrients in winter wheat at BBCH 31 stage against P and K fertilization.level (4-year mean)

Tabela 3. Zawartość składników w liściach pszenicy w fazie BBCH 31 na tle zróżnicowanego nawożenia fosforem i potasem (średnia z 4 lat)

Factors Czynniki		Nutrients Składniki g· kg-1				
		N	P	K	Ca	Mg
Years Lata	2007	32.7^{c}	3.04^{a}	26.2^{b}	1.19^{c}	2.20^{a}
	2008	32.7^{c}	3.04^{a}	26.2^{b}	1.19^{c}	2.20^{a}
	2009	39.4^{b}	2.64^{b}	26.3^{b}	2.60^{b}	1.53^{b}
	2010	44.7^{a}	1.85^{c}	30.4^{a}	3.58^{a}	0.55^{c}
	Control (KA) Kontrola	25.1^{c}	2.47^{cd}	24.0^{b}	1.79^{de}	1.23^{b}
Treatments Obiekty	WPN	38.0^{b}	2.59^{bcd}	28.5^{a}	2.66^{a}	1.62^{c}
	WKN	42.6^{a}	3.06^{a}	24.7^{b}	2.44^{ab}	2.10^{a}
	W25	39.7^{b}	2.50^{cd}	26.8^{ab}	2.18^{bc}	1.74^{c}
	WP50	39.0^{b}	2.65^{bc}	27.7^{a}	1.60^{e}	1.54^{c}
	WK50	38.0^{b}	2.82^{ab}	28.4^{a}	2.33^{abc}	1.60^{c}
	W100	38.4^{b}	2.75^{bc}	29.0^{a}	2.10^{cd}	1.58^{c}
	W100 (.P jako – PAPR. *P as PAPR*)	38.1b	2.33^{d}	28.9^{a}	2.02^{cd}	1.53^{c}
	Interaction Year×Treatment Interakcja Rok×Obiekt	n.s.	s	n.s.	n.s.	n.s.

Means indicated by different letters are different (Tukey's test, p<0.05); ns - not significant; s- significant

Średnie zaznaczone różnymi literami różnią się (Test Tukeya, p<0.05); ns – nieistotnie, s - istotnie

The content of P in plants can also be contingent to the interaction between water-soluble P and that bound in soil, and this dependence is shaped by soil reaction to a big extent (Bar-Yosel, 2003). Comparative evaluation of own data on yields and plant nutritional status at the critical growth stage of plants with those obtained in German investigation (Haneklaus and Schnug 1998) indicates clearly that the system of assessment of plant nutritional status in the depth of vegetation cannot be accepted as comprehensive, and it requires modification with reference to specific regional conditions (soil, climate) which was confirmed by Gaj (2008, 2010).

Mineral fertilization significantly increased K content in wheat leaves when compared to the control and the treatment where this element had not been applied for 10 years (WKN). Increasing rates of K resulted in an increase of plant K contents, of which the highest one was observed in the treatments optimally balanced with regard to nitrogen (W100). Both a level of potassium availability in soil which reflects the status of macronutrient reserves and the extent of plant root system development are important factors which determine plant nutrition with K. In this study, wheat was cultivated at a site with medium content of available K in soil, i.e. 120-150 mg K_2O*kg of soil $^{-1}$. In the treatments where K was not applied (KA and WKN), available macronutrient contents were low in soil and amounted to 100 mg K_2O·kg of soil $^{-1}$, which directly resulted in low K content in the plant. Every agricultural process or else treatment which disturbs nutrition of plants with K decreases plant metabolic activity and adds up to the reduction of nitrogen yield efficiency. Literature data concerning the dependence of plant K content on a rate of this macronutrient in a fertilizer are inconclusive. The results of Kunzova, Hejcman (2010) showed the lack of any direct relationship between the content of available P and K forms in soil and the contents of these elements in the plant. K deficiency at the stage of plant intensive growth results in a number of disturbances in production of constituents of yield structure (Grzebisz 2009). Regardless mineral fertilization level, observed plants showed Ca malnutrition (Table 3), and this was a result of wheat cultivation on acidic soil, reaction of which ranged from pH 4.76 to 4.92 depending on fertilizer treatment applied. Although the plants were optimally nourished with Mg, the analysis of correlation between wheat grain yield and the content of macronutrients in leaves at the beginning of stem elongation stage (BBCH 31) showed significant relationship for Ca in shaping wheat grain yield ($r = 0.36$; $p = 0.041$; $n = 32$). Knowledge on nutritional status of wheat at BBCH 31 stage allows setting up nutritional adjustment. At this stage of wheat growth, there occur deep developmental changes, and that is why the appraisal correctly carried out lets fertilizer adjustment.

In view of plant nutritional status it is important to maintain proper relationships among nutrients. The content of individual nutrients can change with plant age, thus making use of nutrients which provide information on plant physiological status is more relevant for diagnostic purposes (Santa-Maria, Epstain 2001; Nebolsin, et al. 2004). In the present study, there were found significant correlations for the following pairs of nutrients: nitrogen-potassium, nitrogen-phosphorus, nitrogen-magnesium and nitrogen-calcium (Table 4). In case of N:K correlation, there can be stated that the better plants are nourished with K in relation to N the better is their resistance and the higher is the predictive value. The above relationship was also showed by the results of other studies concerning quality wheat (Gaj 2010, 2013). The mechanism of interaction between N and K as well as N and P has been well documented in subject literature (Marschner, et al., 1996; Greenwood and Stone 1998; Broadley, et al., 2004). Uptake of nitrate ions, and then their transport in plants in fact depends on supply of K and requires constant delivery of this nutrient. Potassium is broadly believed to be the nutrient which influences plant growth in cooperation with other elements. The second assessment of winter wheat nutritional status was carried out at the flowering stage (BBCH 65), with the main aim to use plant chemical analyses and biomass estimation for yield predictions. Evaluation of nutrient contents in leaves, stems and ears at the flowering stage showed that leaf N, P and K contents, both for the absolute control and fertilizer treatments decreased when compared to those at BBCH 31 stage (Table 5). The decrease of nutrient contents is the effect of the natural process and results from biomass increase and nutrient movement from vegetative organs into ears, and then their accumulation in grain.

Stepwise regression with backward elimination showed that grain yield (GY) of bread wheat was for the most part determined by the content of K in leaves as well as the content of Ca in ears at BBCH 65 stage as it is presented below by the following regression equations:

$Y(GY) = 1.61*\%K65l – 26.26*\%P65L + 8.61$ $R^2 = 0.49$; $p < 0.00005$; $n = 32$

$Y(GY) = 25.09*\%Ca65k + 3.57$ $R^2 = 0.32$; $p < 0.00081$; $n = 32$

Table 4. Correlation coefficients between nutrient contents in winter wheat leaves at BBCH 31 stage and grain yield (n = 32)

Tabela 4. Współczynniki korelacji między zawartością składników liściach a plonem ziarna pszenicy (n = 32)

Variable Zmienna	Nutrients ($g \cdot kg^{-1}$) Składniki ($g \cdot kg^{-1}$)				
	N	P	K	Ca	Mg
Yield ($t \cdot ha^{-1}$) Plon ($t \cdot ha^{-1}$)	-0.112	0.228	0.210	-0.273	0.364*
N	1	-0.386*	0.518*	0.741*	-0.405*
P	-	1	-0.518*	-0.603*	0.846*
K	-	-	1	0.477*	-0.527*
Ca	-	-	-	1	-0.749*
Mg	-	-	-	-	1

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

The content of N in the organs analyzed at wheat flowering stage decreased as follows: leaves>ears>stems. In case of leaves and ears, a significant increase of N content was recorded only in comparison with the absolute control, whereas fertilizer treatments did not differ from each other. Under conditions of P and K fertilization, there was observed considerably larger differentiation with regard to N content in stems. The highest N content was observed in WKN treatment, and it differed not only from the control, but also from other fertilizer treatments investigated. N content was also significantly differentiated in the years of observation. In case of ears and stems the lowest N contents were observed in the years 2007 and 2008, at which time there were also noted the lowest biomasses of the organs analyzed (Table 9).
The content of P at wheat flowering was differentiated, depending on the organ analyzed and the year of observation. Among the wheat organs investigated, the highest content of this nutrient was found in ears, whereas it was the lowest in stems. Differentiated mineral fertilization had no effect on P content in ears, while significant differences between treatments were observed for leaves and stems (Table 5).
The content of K in wheat organs was significantly differentiated by the experimental factor. Regardless the organ analyzed, the lowest content of K was observed in the absolute control and at the site where potassium fertilization had been omitted for 10 years (WKN) (Table 6).Taking into account differentiated nutrient rates applied K, a level of nutrient availability in soil and K content in wheat at flowering stage, there were found similar relationships in long-term studies carried out in France (Jouany, at al. 1996).The content of nutrients in grain and straw was analyzed at the stage of full ripening (BBCH 89). Both deficiency and excess of mineral elements in cereal grain decrease its biological value, which can unfavorably influence metabolic processes in humans and animals (Gondek 2012).
In case of N, there was observed a significant increase of N content in the plant organs analyzed as a result of mineral fertilization when compared with the control experimental variant. On the other hand, there were no significant differences observed in N contents among the treatments with differentiated levels of P and K

fertilization. Furthermore, N content at full ripening stage was significantly differentiated in the years of investigation. The highest N content was found in the year 2009. Higher nutrient concentration in the plant was associated with low yields (Table 9). Irregular distribution of precipitation in the months falling on the stages of intensive plant growth (April, May and June, Table 2) was the main cause of yield reduction due to disturbances in water and nutrient uptake dynamics. Plants under conditions of water stress being a result of drought built up relatively lower vegetative mass, and consequently larger nitrogen pool was accumulated in grain. It has been well documented that trimming spikes after anthesis increases grain protein concentration (Jenner 1980). High temperatures cause fast hydrolysis of proteins in leaves, therefore grain ripening stage is short, and hence grain mass is low but contains large contents of nitrogen (proteins) (Corbellini, et al. 1998; Daniel and Triboi 2002; Flagella, at al. 2010).

When speaking about grain N content, there should be attention drawn to the content of phosphorus in grain. A number of authors emphasize positive effects of increasing P content in grain, especially those from consumer point of view. Grain P is a valuable source of this nutrient for humans and animals. The additional benefit of high P contents in grain is a possibility of obtaining higher grain yields with better germination capability, which is particularly important in reproduction of sowing material (Bolland, and Baker 1988; Manske, et al. 2001; De-Marco, 1990). A decrease of P contents results in reduction of grain anti-nutritional factors such as phytic acid Batten (1986). In the present study, the content of P was differentiated depending on a rate of the nutrient applied as fertilizer. Significantly highest increase of P in wheat grain was observed for the treatment with optimal fertilization with regard to nitrogen (W 100%). N nutritional status of the plant determines P uptake, and both elements are included into the processes of photosynthesis, protein biosynthesis as well as nitrogen (N_2) fixation. The issues concerning N and P interactions have been discussed in a number of papers (Kim, 2003; Prystupa, et al. 2004; Sadras, 2006; Summer, Farina 1986; Zhang, et al. 2007). Rychter, Randall (1994) stress that prolonged P deficiency in the plant reduces the pool of energy compounds ATP, and then as a result uptake of nitrate nitrogen ($N\text{-}NO_3$) is limited. On the other hand, N excess at lacking phosphorus triggers the first symptoms of P deficiency. Under field conditions, there remains a question on a role of N/P interactions in shaping improvement of nutrient utilization. The processes of nitrogen-phosphorus interactions are determined to a big extent by soil and climatic conditions (Summer, Farina 1986). In the present study, the course of weather conditions significantly reduced the content of P in grain. In the present study, water stress decreased mobility of phosphate ions, and regardless of their concentration in soil the content of this nutrient in the plant was lower when compared to the years with optimal water conditions. Furthermore, water deficiency in soil instigates the processes of solidification, and then crystallization of bounds between phosphorus and aluminum as well as calcium, which consequently leads to the reduction of soil content of this nutrient available for plants (Grzebisz, 2008). The analysis of correlations between N and P contents in wheat grains performed in this study showed significant negative correlation ($r = -0.454$; $p = 0.09$; $n = 32$).

The contents of K, Ca and Mg in wheat grain were significantly differentiated in the years of observations and also due to fertilization with variable P and K rates (Table 6). Under mineral fertilization, there was observed a significant increase of K content in grain, whereas differences among the treatments with variable rates of K were ambiguous. The lack of significant differences in K content in wheat grain when treated with different rates of this nutrient was also reported by Jouany, et al. 1996. The highest content of Mg was observed at the site with no K treatment (WKN), which indicates antagonistic relationship between K and Mg. Literature data point out that intensive fertilization with K can sometimes result not only in changes of K content but also of other nutrients, which is followed by their deficient or excessive concentration. This concerns especially Ca and Mg. In the present study, there was observed the state when the lack of K fertilization encouraged Mg uptake.

In grain, not only contents of particular nutrients, but at the outset - proper relations between nutrients of key importance in evaluation of consumptive and fodder value, play an essential role. In the grain analyzed, there were evaluated the following relations between nutrients: N:P and Ca:Mg (Table 7). In both cases, relations between nutrients were significantly differentiated in the years of observations. According to Duivenbooden, et al. (1996), the optimal ratio N/P should amount for about 7 (P/N = 0.14). The ratio of N to P for the wheat analyzed was 8.9 and ranged from 7 to 10. Obtained N/P relations in wheat were comparable with the results of Takahashi (2007) who observed N/P relation in cereals ranging from 5.8 to 9.9. Sadras (2006) studied N/P relation in cereals and showed that more than 40% of investigated plants which reached the highest yield were characteristic of a narrow range of N/P relation which was from 4 to 6. In the present study, a level of phosphorus and potassium fertilization had no significant effect on N/P relation in wheat grain. On the other hand, there was shown significant differentiation of N:P ratio in the years of observation. On the other hand, regardless the year of observations, diversified P and K rates significantly differentiated relations between the following nutrient pairs in grain: N:Mg, N:Ca, K:Mg.

Next to evaluation of nutrient contents, biomass determination is a good tool in diagnostic prediction of yield. In practice, evaluation of aboveground biomass is most often used, since this is a measurable indicator which can additionally be referenced to a particular plant growth stage - the so called indicative stage (Grzebisz 2008). In the present study, wheat biomass evaluated in specified growth stages was significantly differentiated by the experimental factor at the stage of flowering. At the beginning of stem elongation and ripening stages, there was observed increased biomass only in comparison with the control, whereas fertilizer treatments were not different from each other (Table 8). Correlation analysis which took into account relations between overall plant biomass, the organs analyzed at BBCH 31 and BBCH 65 stages and wheat grain yield (Table 9) showed significant relationships only for wheat leaves in the abovementioned stages. This can be useful as an element of diagnostics of grain yield.

Conclusions

1. Evaluation of wheat nutritional status at stem elongation stage showed plant malnutrition with regard to phosphorus, potassium and magnesium. Regression analysis on the relationship between grain yield and nutritional status showed significant dependency only for magnesium.
2. Regardless the rate of applied nutrients and the year of observation, the level of fertilization with phosphorus and potassium had no significant effect on shaping the differences in nitrogen contents in wheat grain and straw.
3. The content of phosphorus, potassium, calcium and magnesium in grain as well as that of phosphorus and calcium in straw at wheat grain ripening stage were determined mainly by weather conditions in the years of observations.

4. The level of fertilization with phosphorus and potassium had no significant effect on N:P and N:K relations in grain, however it significantly differentiated the following nutrient pairs N:Mg, N:Ca and K:Mg. Differentiated P and K mineral fertilization significantly increased plant biomass at the critical growth stages when compared to the control, whereas significant differences among the treatments were observed only at wheat flowering stage.
5. The analysis of correlation between grain yield and biomass of wheat organs at BBCH 31 and BBCH 65 stages indicated the highest correlation coefficient values for dry leaf matter at both stages, which points out to great prognostic usefulness of these organs.

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Table 5. Content of nutrients in winter wheat organs at flowering stage (BBCH 65) against P and K fertilization level (4-year mean)

Tabela 5. Zawartość składników w organach pszenicy w fazie kwitnienia pszenicy (BBCH 65) na tle zróżnicowanego nawożenia fosforem i potasem (średnia z 4 lat)

Factors Czynniki		Nutrients g*kg^{-1} Składniki g*kg^{-1}														
		N			P			K			Mg			Ca		
		Leaves Liście	Stalks Źdźbła	Ears Kłosy	Leaves Liście	Stalks Źdźbła	Ears Kłosy	Leaves Liście	Stalks Źdźbła	Ears Kłosy	Leaves Liście	Stalks Źdźbła	Ears Kłosy	Leaves Liście	Stalks Źdźbła	Ears Kłosy
Years Lata	2007	27.6^{b}	9.5^{c}	17.2^{c}	2.16^{a}	1.59^{a}	2.5^{a}	19.8^{b}	15.1^{b}	11.1^{b}	2.64^{a}	0.67^{b}	0.8^{b}	2.93^{b}	1.09^{b}	1.3^{a}
	2008	26.1c	8.7^{d}	18.1^{b}	1.53^{c}	0.85^{c}	2.5^{a}	15.4^{c}	16.4^{b}	8.2^{c}	1.57^{b}	0.56^{b}	0.6d	2.52^{c}	0.47^{c}	1.0^{b}
	2009	32.7^{a}	15.1^{a}	22.0^{a}	1.93^{c}	1.21^{b}	2.1^{b}	11.9d	26.3^{a}	6.2^{d}	2.48^{a}	1.51^{a}	0.1^{a}	2.82^{b}	2.60^{a}	0.7^{c}
	2010	23.1^{d}	11.2^{b}	22.2^{a}	2.20^{a}	1.51^{a}	1.7^{c}	23.2^{a}	11.3^{c}	13.3^{a}	0.83^{c}	0.18^{c}	0.9^{c}	4.66^{a}	1.03^{b}	1.3^{a}
Treatments Obiekty	Kontrola Control (KA)	14.1^{c}	6.60c	15.4^{b}	1.87^{bc}	1.07^{b}	2.10^{a}	10.8d	12.0^{c}	8.2^{b}	1.24^{d}	0.48^{d}	0.7^{b}	2.24^{c}	0.98c	1.1^{bca}
	WPN	30.0^{a}	11.8^{ab}	20.0^{a}	1.7^{2c}	1.22^{ab}	2.3^{a}	18.9^{ab}	19.2^{a}	10.4^{a}	1.91^{bc}	0.84^{b}	0.8^{ab}	3.14^{b}	1.35^{ab}	1.1^{bca}
	WKN	29.5^{a}	12.6^{a}	21.3^{a}	2.08^{ab}	1.39^{a}	2.1^{a}	15.8^{c}	14.3^{c}	9.5^{ab}	2.40^{a}	1.24^{a}	0.8^{ab}	3.90^{a}	1.53^{a}	1.2^{a}
	W25	26.0^{b}	11.1^{b}	20.5^{a}	1.88^{abc}	1.19^{b}	2.2^{a}	17.1^{bc}	16.8^{b}	9.6^{ab}	1.66^{c}	0.74^{bc}	0.8^{ab}	3.48^{b}	1.47^{ab}	1.0^{bc}
	WP50	29.1^{a}	11.5^{b}	20.3^{a}	1.98ab	1.37^{a}	2.2^{a}	20.1^{a}	19.3^{a}	10.4^{a}	1.82^{c}	0.60^{cd}	0.8^{ab}	3.25^{b}	1.27^{ab}	1.1^{ba}
	WK50	30.4^{a}	12.0^{ab}	20.4^{a}	2.10^{ab}	1.36^{a}	2.3^{a}	18.9^{ab}	18.9^{ab}	10.5^{a}	1.66c	0.65bcd	0.8^{ab}	3.25^{b}	1.53^{a}	1.1^{bc}
	W100	29.3^{a}	11.9^{ab}	20.6a	2.11^{a}	1.34^{a}	2.1^{a}	19.1ab	18.0^{ab}	10.5^{a}	1.94^{bc}	0.66^{bcd}	0.7^{b}	3.22^{b}	1.24^{bc}	1.2^{ba}
	W100 (.P jako – PAPR. P as PAPR)	30.5^{a}	11.7^{ab}	20.8^{a}	1.89^{abc}	1.40^{a}	2.2^{a}	20.1^{a}	19.8^{a}	9.8^{a}	1.79^{c}	0.62^{cd}	0.7^{b}	3.36^{b}	1.23^{bc}	1.0^{c}
Interaction Year×Treatment Interakcja Rok×Obiekt		ns	ns	ns	ns	s	s	ns	ns	s	ns	s	s	ns	ns	s

Means indicated by different letters are different (Tukey's test, p<0.05); ns - not significant, s- significant Średnie zaznaczone różnymi literami różnią się (Test Tukeya, p<0.05); ns – nieistotnie, s - istotnie

Table 6. Contents of macronutrients in winter wheat grain and straw according as K and P fertilization level (4-year mean)

Tabela 6. Zawartość makroskładników w ziarnie w słomie pszenicy na tle zróżnicowanego poziomu nawożenia P i K

Factors Czynniki		Nutrients g*kg^{-1}Składniki g*$^{-1}$									
		N		P		K		Ca		Mg	
		Grain Ziarno	Straw Słoma	Grain Ziarno	Straw Słoma	Grain Ziarno	Straw Słoma	Grain Ziarno	Straw Słoma	Grain Ziarno	Straw Słoma
Years Lata	2007	18.6^{c}	5.4^{c}	2.81^{a}	0.37^{b}	4.98^{a}	7.2^{a}	0.35^{b}	0.98^{bc}	1.22^{b}	0.035^{b}
	2008	20.5^{b}	9.2^{b}	2.20^{b}	0.15^{d}	3.17^{c}	6.4^{b}	0.21^{c}	0.84^{c}	1.23^{b}	0.042^{a}
	2009	23.5^{a}	10.3^{a}	1.61^{d}	0.77^{a}	4.61^{b}	4.9^{d}	0.19^{c}	1.12^{b}	1.53^{c}	0.036^{b}
	2010	18.2^{c}	4.2^{d}	1.90^{c}	0.30^{c}	4.78^{ab}	5.6^{c}	0.55^{a}	2.66^{a}	0.65^{c}	0.019^{c}
Treatments Obiekty	Control (KA) Kontrola	17.4^{b}	5.5^{b}	2.01^{c}	0.41^{abc}	3.89^{c}	4.1^{c}	0.33^{b}	1.07^{b}	1.09^{bc}	0.31^{bc}
	WPN	20.8^{a}	7.4^{a}	2.05^{c}	0.35^{bc}	4.53^{ab}	6.7^{a}	0.32^{bc}	1.40^{a}	1.18^{bc}	029^{c}
	WKN	20.5^{a}	7.6^{a}	2.20^{c}	0.43^{ab}	4.55^{ab}	5.1^{b}	0.34^{b}	1.53^{a}	1.36^{a}	0.38^{ab}
	W25	20.8^{a}	8.0^{a}	2.06^{bc}	0.36^{abc}	4.46^{abc}	5.4^{b}	0.31^{bc}	1.46^{a}	1.25^{ab}	0.40^{a}
	WP50	20.5^{a}	7.5^{a}	2.25^{ab}	0.36^{abc}	4.36^{abc}	6.7^{a}	0.42^{a}	1.38^{a}	0.99^{c}	0.33^{abc}
	WK50	20.8^{a}	7.2^{a}	2.07^{bc}	0.45^{ab}	4.17^{bc}	6.8^{a}	0.26^{c}	1.47^{a}	1.14^{bc}	0.29^{c}
	W100	20.3a	7.7^{a}	2.09bc	0.46^{a}	4.33^{abc}	6.9^{a}	0.27^{bc}	1.45^{a}	1.01^{c}	0.27^{c}
	W100 (,P jako – PAPR, P as PAPR)	20.7^{a}	7.5^{a}	2.31^{a}	0.41^{abc}	4.79^{a}	6.9^{a}	0.33^{b}	1.44^{a}	1.21^{ab}	0.38^{ab}
Interaction Year×Treatments Interakcja Rok×Obiekt		ns	ns	s	s	s	ns	s	s	s	ns

Means indicated by different letters are different (Tukey's test, $p<0.05$); ns - not significant, s- significant
Średnie zaznaczone różnymi literami różnią się (Test Tukeya, $p<0.05$); ns – nieistotnie, s - istotnie

Table 7. Relations between nutrient contents in grain according as differentiated mineral fertilization with P and K

Tabela 7. Relacje pomiędzy zawartościami składników w ziarnie na tle zróżnicowanego poziomu nawożenia mineralnego P i K

Treatments Obiekty	N:P	N:K	N:Mg	N:Ca	K:Mg
Control (KA)Kontrol	9.80[a]	4.75[a]	17.69[b]	59.22b	3.90b
WPN	10.84[a]	4.83[a]	18.81[ab]	78.07[b]	4.16[ab]
WKN	9.92[a]	4.76[a]	17.33[b]	71.13[b]	3.93[b]
W25	10.60[a]	4.93[a]	20.19[ab]	79.16[b]	4.46[ab]
WP50	9.83[a]	5.08[a]	22.45[a]	70.45[b]	5.30[a]
WK50	10.70[a]	5.14[a]	19.52[ab]	120.84[a]	4.08[b]
W100	10.39[a]	4.92[a]	22.20[a]	110.37[a]	4.97[ab]
W100 (P as PAPR) (P jako – PAPR)	9.46[a]	4.70[a]	19.05[ab]	102.31[a]	4.63[ab]
Interaction Year×Treatment Interakcja Rok×Obiekt	s	s	s	s	s

Means indicated by different letters are different (Tukey's test, p<0.05); s- significant
Średnie zaznaczone różnymi literami różnią się (Test Tukeya, p<0.05); s - istotnie

Table 8. Simple correlation coefficients between winter wheat yield and plant total dry matter (n = 32)

Tabela 8. Współczynniki korelacji prostej pomiędzy plonem ziarna pszenicy a biomasą całkowitą roślin w analizowanych fazach rozwojowych (n= 32)

Growth stage Faza rozwojowa	Total biomass Biomasa całkowita	Plant organs Organy rośliny		
		Leaves Liście	Stalks Źdźbła	Ears Kłosy
BBCH 31	0.46*	-	-	-
BBCH 65	0.21	0.57*	0.22	-0.014

*correlation significant at p < 0.05 * korelacja istotna na poziomie p < 0.05

Table 9. Effects of differentiated P and K mineral fertilization on biomass of winter wheat at critical development stages and grain yield

Tabela 9. Wpływ zróżnicowanego nawożenia mineralnego fosforem i potasem na wielkość biomasy w fazach krytycznych oraz plon ziarna pszenicy ozimej

Factors Czynniki		Plant biomass (t ha^{-1}) Biomasa roślin (t ha^{-1})		
		BBCH 31	BBCH65	BBCH92(grain) (ziarno)
Years Lata	2007	1.19^{c}	5.07^{d}	6.10^{b}
	2008	2.68^{a}	7.36^{c}	7.71^{a}
	2009	2.32^{b}	8.23^{b}	5.18^{c}
	2010	1.22^{c}	10.73^{a}	6.21^{b}
Treatments Obiekty	Kontrola Control (KA)	0.97^{b}	4.76^{c}	4.44^{b}
	WPN	1.96^{a}	8.29^{ab}	6.74^{a}
	WKN	1.92^{a}	8.27^{ab}	6.75^{a}
	W25	1.87^{a}	7.69^{b}	6.34^{a}
	WP50	2.06^{a}	8.79^{a}	6.55^{a}
	WK50	2.03^{a}	8.41^{ab}	6.27^{a}
	W100	1.90^{a}	7.93^{ab}	6.89^{a}
	W100 (P jako – PAPR. P as PAPR)	2.12^{a}	8.65^{a}	6.45^{a}
Interaction Year×Treatment Interakcja Rok×Obiekt		ns	ns	ns

Means indicated by different letters are different (Tukey's test, p<0.05); ns- not significant

Średnie zaznaczone różnymi literami różnią się (Test Tukeya, p<0.05); ns – różnica nieistotns