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EFFECT OF BALANCED NITROGEN FERTILIZATION IN FOUR- YEAR ROTATION ON PLANT PRODUCTIVITY

WPŁYW ZBILANSOWANEGO NAWOŻENIA AZOTEM NA PRODUKCYJNOŚĆ ROŚLIN W CZTERO-LETNIM ZMIANOWANIU

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Abstract

Increased nitrogen use efficiency, NUE, in crop plant production is the main challenge for agriculture in this century. Any success in this objective achievement requires to take into account not only phosphorus and potassium but also secondary nutrients, such as magnesium and sulfur, at least. In order to check this hypothesis a series of annual field experiments were conducted in 2005, 2006, 2007 and 2006, testing in the four course rotation response of following crops: maize → spring barley → winter oil-seed rape → winter wheat to increasing level of nitrogen nutritional balance imposed by set of treatments comprised potassium and magnesium. The obtained results clearly indicated on maize as the most productive crop, irrespective of the imposed fertilizing system. The highest yields of the tested crops were harvested on plots fertilized with NPK and Kieserite, provide that potassium was applied as Korn-Kali. Effects of the imposed systems of fertilizer N balancing have been assessed by means of two NUE indices, such as: (i) partial factor productivity of fertilizer nitrogen (PFP_N) and agronomic net efficiency of fertilizer nitrogen (AE_N). Both indices were useful in making a reliable evaluation of tested treatments, but the AE_N was more conspicuous as a NUE index. The most pronounced effect of the applied nutrients on yield development was through improvement of kernel/grain number per plant. This fact indirectly stresses on the importance of the period extending from the stage of ear growth to the stage of kernel/grain growth as decisive for final grain yield establishment. The net balance of plant available potassium and phosphorus showed that their net surplus with respect to yield response was negative, in turn indicating on magnesium as a nutrient required to reach nutritional balance of N, P, K in high-yielding crops.

Keywords: balance in soil, AE_N, magnesium, nitrogen efficiency, PFP_N, potassium

Streszczenie

Zwiększona efektywność azotu w uprawie roślin jest głównym wyzwaniem rolników w obecnym stuleciu. Jakikolwiek sukces wymaga uwzględnienia nie tylko fosforu i potasu, lecz także składników drugoplanowych, takich jak magnez i siarka. Celem sprawdzenia postawionej hipotezy w latach 2005, 2006, 2007 i 2008 przeprowadzono serię jednorocznych doświadczeń polowych, testując w czteroletnim zmianowaniu reakcję następujących po sobie roślin: kukurydza → jęczmień jary → rzepak ozimy → pszenica ozima na wzrastający poziom zbilansowania azotu nawozowego, określony przez układy doświadczalne zawierające potas i siarczan magnezu. Uzyskane wyniki badań jednoznacznie wskazały na kukurydzę, jako uprawę najbardziej produkcyjną, niezależnie od testowanego systemu nawożenia. Największe plony roślin uzyskiwano z kombinacji nawożonej NPK z kizerytem, pod warunkiem, ze potas stosowano w formie Korn-Kali. Skutki plonotwórcze testowanego systemu bilansowania azotu nawozowego oceniono na podstawie dwóch indeksów: (i) produkcyjności brutto azotu nawozowego (PFP_N) i (ii) efektywności azotu nawozowego netto (EA_N). Oba indeksy okazały się przydatne w ocenie efektywności azotu, lecz EA_N okazał się statystycznie lepszym wskaźnikiem. Najbardziej jednoznaczną reakcję na testowane sposoby bilansowania azotu nawozowego, istotne dla końcowego plonu ziarna, wykazała liczba ziarniaków w kłosie/kolbie. Ten fakt wskazuje na znaczenie okresu rozwoju rośliny, rozciągający się od stadium wzrostu kłosa do stadium wzrostu ziarniaka, jako na krytyczny dla formowania plonu ziarna. Przedstawiony netto bilans przyswajalnego potasu i fosforu wykazał, że nadmiar obu składników, w stosunku do reakcji plonotwórczej rośliny, wymaga także zrównoważenia pośrednio wskazując na magnez, jako składnik niezbędny dla uzyskania bilansu żywieniowego wysoko-plonujących roślin uprawnych.

Słowa kluczowe: bilans w glebie, AE_N, efektywność azotu, magnez, PFP_N, potas

Streszczenie szczegółowe

Zwiększona efektywność azotu w uprawie roślin jest głównym zadaniem rolnictwa w obecnym stuleciu. Uzyskanie założonego celu wymaga jednakże powszechnego uwzględnienia w systemie nawożenia roślin uprawnych nie tylko fosforu i potasu, lecz także składników drugoplanowych, takich jak magnez i siarka. Celem sprawdzenia postawionej hipotezy w latach 2005, 2006, 2007 i 2008 przeprowadzono serię jednorocznych doświadczeń polowych, testując w czteroletnim zmianowaniu reakcję następujących po sobie roślin: kukurydza → jęczmień jary → rzepak ozimy → pszenica ozima na wzrastający poziom zbilansowania azotu nawozowego, określony zarówno przez stosowanie nawozów zawierających potas, jak i siarkę z magnezem. Uzyskane wyniki badań jednoznacznie wskazały na kukurydzę, jako uprawę najbardziej produkcyjną, niezależnie od testowanego systemu nawożenia. W porównaniu do plonów kukurydzy na obiekcie kontrolnym, który wynosił 5.65 t ha^{-1} (jednostek zbożowych) pozostałe rośliny, uprawiane kolejno w zmianowaniu, czyli

jęczmień, rzepak, pszenica plonowały odpowiednio na poziomie 40%, 58%, 62%. Największe plony testowanych roślin uzyskano na kombinacji nawożonej NPK z MgS, pod warunkiem, że potas stosowano w formie Korn-Kali (NPK+3MgS). Efektywność plonotwórczą azotu dla założonego systemu bilansowania azotu nawozowego oceniono na podstawie dwóch indeksów: (i) produkcyjności brutto azotu nawozowego (PFP_N) i (ii) efektywności azotu nawozowego netto (EA_N). Średnie wartości indeksów PFP_N w porównaniu do obiektu NP zwiększyły się na obiektach NPK+1MgS, NPK+2MgS i NPK+3MgS, odpowiednio o 10%, 20% i 22%. Drugi z indeksów, EA_N, wykazał zdecydowanie większą reakcję testowanych roślin na wprowadzone poziomy nawożenia MgS. Istotne różnice względem kontroli absolutnej dla tego indeksu uzyskano tylko dla kukurydzy i rzepaku. Na obiekcie NPK+3MgS w porównaniu do NP wartości EA_N zwiększyły się odpowiednio o 64% i 75%. Spośród dwóch ocenianych elementów struktury plonu ziarna, testowanych dla zbóż i kukurydzy, jednoznaczną reakcję na badane sposoby bilansowania azotu nawozowego wykazała liczba ziarniaków w kłosie/kolbie. Ten fakt jednoznacznie wskazuje na znaczenie okresu rozwoju roślin zbożowych, rozciągający się od stadium wzrostu kłosa do stadium wzrostu ziarniaka, jako krytyczny dla formowania plonu ziarna. Bilans netto przyswajalnego potasu i fosforu w glebie wykazał nadmiar obu składników w stosunku do reakcji plonotwórczej rośliny, prowadząc tym samym do spadku plonu ziarna w miarę wzrostu wartości salda bilansowego. Natomiast saldo bilansowe magnezu wykazało dodatni związek z plonem ziarna. Można więc stwierdzić, że w procedurze bilansowania podstawowych składników pokarmowych należy poddać nie tylko azot, lecz także podstawowe składniki żyzności gleby, jakimi są fosfor i potas. W omawianym przypadku składnikami wymaganymi dla uzyskania stanu zbilansowania żywieniowego testowanych roślin okazały się także magnez i siarka.

Introduction

Nitrogen use efficiency (NUE) depends on many external factors governing nitrogen uptake and utilization by crop plants. All these factors are responsible for rate of nitrogen uptake in critical stages of currently grown crop, in turn affecting its biomass and expression of yield forming elements. Insufficient supply of nitrogen during the kernel number per plant (KNP) set up significantly decreases the physiological sink capacity of all plants producing grain or seed yield. In this group of plants the major critical period extends from the stage of ear growth (BBCH 51) up to the stage of juvenile grain formation (BBCH 71). The yield reduction is only partly compensated by increasing weight of seeds/kernels during the post-flowering period (Evans and Wardlow, 1976; Janssen 1998; Otequi and Bonhomme, 1998; Gambin et al., 2006).

In agronomic practices, there are considered several steps focused on balanced use of fertilizer nutrients. The major one assumes proper use of fertilizer nitrogen in accordance to the formula termed as the rule of three fertilizing rights, related to adequate N use and reported as adequate i) rate, ii) timing and iii) method of fertilizer nitrogen application. This formula is properly fulfilled only under set of conditions, which are as follows: i) soil pH adjusted to optimum level for the most sensitive crop in a given rotation; ii) immobile nutrients such as potassium and phosphorus are not limiting growth factors; iii) other nutrients, such as magnesium, sulfur and micronutrients are applied in quantities supporting N utilization efficiency. The recent study conducted by Subedi and Ma (2009) in Canada revealed that shortage of potassium reduces grain yield of maize by 13%. In the Central-Eastern European countries during the last two decades supply of nitrogen has not been balanced by potassium and phosphorus, in turn seriously limiting yields of cereals and oils-seed rape (Grzebisz, 2009).

In Poland yields of critical seed crops are much more below their yielding potential. There are two principal reasons of this state. The first one refers to soil and climatic conditions, which are much worse than in the west part or Europe. The second one relates to currently fertilizing practices, which is generally N oriented. In Poland, at the beginning of the XXI century the consumption ratio of main nutrient N: P_2O_5 : K_2O was as follows: 1 : 0.3 : 0.4, while it should be at the level of 1 : 0.5 : 1.0, at least (Grzebisz et al., 2010).

The main objective of the conducted study was to evaluate nitrogen use efficiency in four course crop rotation: maize → spring barley → oil-seed rape → winter wheat and yield response to conditions of increasing supply of nutrients balancing nitrogen fertilizer.

Materials and methods

A four course rotational field trial was established in 2005. Study on four crops grown in rotation**:** maize → spring barley → oil-seed rape → winter wheat (cultivars: Eurostar, Rubinek, Californium, Zyta) response to increasing supply of nutrients balancing fertilizer nitrogen were carried out during four consecutive growing seasons 2005, 2006, 2007 and 2008 at the RGD Brody (Poznań University of Live Sciences Experimental Station; 16°28'E i 52°44'N). The experimental trial was set up on a soil originated from loamy sand underlined by light loam soil and classified accordingly to Polish norms as the IVa class, very good rye complex and agronomical category – light soil. The field trial arranged as one-factorial design, replicated four times, was consisted of six treatments:

1. Control (absolute control, i.e. no applied fertilizers), (acronym Control),
2. NP (applied only nitrogen and phosphorus),
3. NPK (basic set of nutrients, K applied as KCl),
4. NPK + 1MgS (K and Mg, S applied as Korn-Kali),
5. NPK + 2MgS (K applied as KCl; Mg, S as Kieserite),
6. NPK + 3MgS (K applied as Korn-Kali; Mg, S as Korn-Kali and Kieserite).

Rates of nutrients incorporated to each crop during the rotation course are presented in Table 1. Formulation of fertilizers were as follows: (i) phosphorus - SSP (single superphosphate, 18% P_2O_5) (ii) potassium, muriate of potash (60% K_2O) in the third and fifth treatment and as Korn-Kali (40% K_2O, 6% MgO, 3% Na, 4% S) the fourth and sixth treatment; (iii) Mg as Kieserite (25% MgO, 20% S) – fifth and sixth treatment and as component of Korn-Kali – fourth and sixth treatment); (iv) nitrogen as ammonium nitrate (34% N). The first rate of nitrogen up to 100 kg N ha^{-1} was always applied before seed-bed preparation and the second one fulfilling the total experimental design in accordance to each crop practices. Herbicides and all other agronomic practices were applied according to the standard for each crop.

The individual plot size was 50 m^2. At maturity crops were harvested from area of 15 m^2. Total yields were adjusted to 14% moisture content in cereals and to 8% in oil-seed rape. All yields has been equalized and presented as cereal unit (CU).

Table 1. Dose of nutrients applied in the four-year rotation
Tabela 1. Dawka składników pokarmowych zastosowanych w czteroletnim zmianowaniu

Treatments, Warianty	N	P_2O_5	K_2O kg ha^{-1}	MgO	S
Control	0	0	0	0	0
NP	160/100/140/150	90/40/70/40	0	0	0
NPK	160/100/140/150	90/40/70/40	200/80/160/80	0	0
NPK+1MgS	160/100/140/150	90/40/70/40	200/80/160/80	30/12/24/12	20/8/16/8
NPK+2MgS	160/100/140/150	90/40/70/40	200/80/160/80	40/30/30/30	32/24/24/24
NPK+3MgS	160/100/140/150	90/40/70/40	200/80/160/80	70/42/54/42	52/32/40/32

Consecutive crops: maize/ spring barley/ oil-seed rape/ winter wheat
Kolejne rośliny: kukurydza/ jęczmień jary/ rzepak ozimy/ pszenica ozima

Partial factor productivity of fertilizer nitrogen (PFP_N) and agronomic efficiency of fertilizer nitrogen (AE_N) were calculated in accordance to the formulas (Novoa and Loomis, 1981):

$$PFP_N = GY_N / D_N \qquad [\text{kg CU} \cdot \text{ha}^{-1}]$$

$$AE_N = (GY_N - GY_0)/D_N \qquad [\text{kg CU} \cdot \text{kg N}^{-1}]$$

where:
GY_N – yield of grain harvested on plots fertilized with N, kg CU ha^{-1}
GY_0 – yield of grain harvested on the control plot, kg CU ha^{-1}
D_N – rate of the applied nitrogen, in kg N ha^{-1}.

The experimentally obtained data were subjected to conventional analysis of variance using STATISTICA 8. The least significant difference values (LSD at P = 0.05) were calculated to establish the significance of mean differences (Tukey's test). The simple regression procedure was used to determine relationships occurring between the studied plant and soil characteristics.

Results and discussion

General growth conditions

General growth conditions comprise two sets of factors: i) weather course in each growing season and ii) soil fertility level. The first refers to temperature and precipitation courses. In the 2005 season, temperature was variable, but a significant rise in comparison to long-term averages occurred only in July. The temporary semi-drought conditions took place a month earlier, in June. Temperature raise concomitant with sufficient water supply around maize flowering created very good conditions for the kernel number per plant set up. The second crop in rotation, spring barley, experienced deep drought and heat stress, which affected plants in June and July. Therefore, stressful effect of unfavorable weather on grain set was the main reason of only medium level of harvested yields. The third crop, oil-seed rape experienced for the most of spring's vegetation very good temperature conditions. Stress conditions due to water shortage revealed in May, the decisive month for the final number of squirrels silique establishment. Winter wheat, the fourth crop in the studied rotation, experienced water shortages for the most of the spring growing period. The most stressful conditions took place in May and June, in turn seriously affecting basic elements of yield structure, i.e. number of ears and grains per an ear.

The second set of growth conditions refers to soil fertility level. Generally, as presented by soil reaction and content of available phosphorus, potassium and magnesium, the growth conditions can be classified as very good, significantly supporting plant growth under stressful weather conditions, which dominated in three of four years of the conducted study.

Yields and nitrogen use efficiency

Yield of any crop plant harvested on the control plot, i.e. without any supply of fertilizers, including nitrogen is the best indicator of natural soil fertility level. As presented in Figure 1 maize grown on the control plot produced 5.65 t CU ha^{-1}. This figure represents the average level of maize yields harvested in Poland in the last decade, indirectly stressing on the very high level of natural soil fertility. Yield performance on the control plot by other three subsequently cultivated crops, such as barley, oil-seed rape and wheat were much lower, contributing to 40%, 58% and 62% of maize achievement, respectively. The found out-yielding effect of maize was also attributed to all tested fertilizing treatments, but keeping plant specific order: spring barley < oil-seed rape < winter wheat.

Among the studied fertilizing treatments, application of nitrogen and phosphorus (i.e., NP treatment) exerted the greatest effect on plant yield. Yield increase as influenced by this factor varied from 45% (for maize) to 70% in the case of barley. Potassium, magnesium and sulphur fertilization influenced the least plant yield, as compared to the NP treatment, (Figure 1). Moreover, the effect of these fertilizers was mostly dependent on plant species, of which oilseed rape and maize responded the best. With respect to both plants, a significant yield increase was obtained in treatments, where potassium was applied and also the highest rate of magnesium and sulphur (NPK+3MgS), as compared to the NP treatment. The found high yielding effect of Korn-Kali (a special potassium fertilizer formulation containing also Mg and S) can be related to date of its application, which for winter crops took place in autumn, whereas Kieserite was added to each crop in spring. The extra yield increase can be explained by the fact, that small amount of early added magnesium and sulfur may seriously affect winter crops, such as oil-seed rape and wheat, growth during their spring regrowth. Yield response of maize to this type of K+MgS fertilizer can also be explained by special kind of interaction occurring between two components of this fertilizing combination.

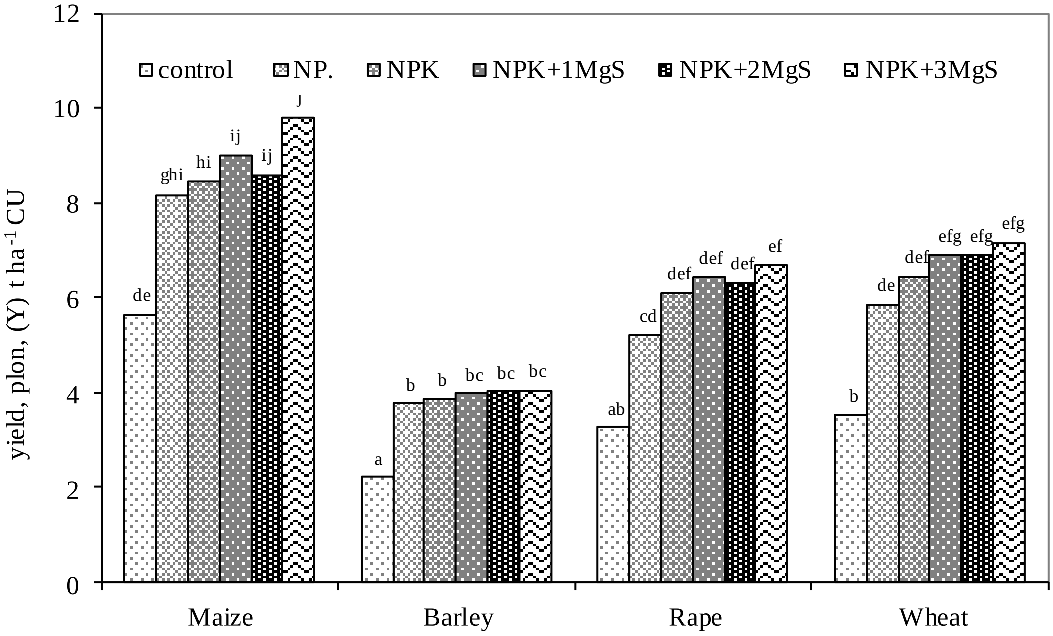

Figure 1. Effect of balanced N fertilization on yield (CU) of crops grown in four year rotation; means following the same letter were not significantly different at α=0.05
Rycina 1. Wpływ zrównoważonego nawożenia azotem na plon (CU) roślin w czteroletnim zmianowaniu; średnie z tą samą literą nie różniły się istotnie na poziomie α=0,05

There has been studied two indices of nitrogen use efficiency, partial factor productivity of fertilizer nitrogen (PFP_N) and agronomic efficiency of fertilizer nitrogen, AE_N, both based on yearly, i.e. crop specific data sets, to evaluate nitrogen use efficiency of applied MgS fertilizers. Maize crop showed a tremendous response to step by step rising N balance. In comparison to the NP treatment crops receiving sub-optimal MgS supply increased PFP_N by 10% and those fertilized with supra-optimal MgS rate by *ca* 20%. The same trend but much lower increase of PFP_N indices was found for winter oil-seed rape. For winter wheat, taking into account the best yielding treatments, the PFP_N raised up by 22% in comparison to the NP plot, but it was not significant (Table 2).

Generally, at every step of N fertilizer nutritional balancing, an increase of the AE_N was noted (Table 3). The highest values of this index have been, irrespectively of the growing crop, attributed to the NPK+3MgS treatment. However, significant differences refer only for maize and oil-seed rape. In maize, the noted AE_N increase reached almost 64% and in oil-seed rape 75% in comparison to the respective NP treatment. Both classical cereal crops also showed high responses to this set of fertilizers, amounting to 20% for spring barley and to 56% for winter wheat, but they were not significant. The found positive effect of magnesium sulfate application on maize yield corroborates a very recent report presented by Szulc (2010). This author showed high magnesium fertilizer effect on the studied nitrogen use efficiency indices, but only under conditions of low N fertilizer rates. Therefore, it can be concluded, that the AE_N index allows to discriminate the tested system of magnesium applications, with very high reliability.

Table 2. Effect of increasing N balancing on the partial factor productivity of fertilizer nitrogen, PFP_N of fertilizer nitrogen, kg CU kg^{-1} N
Tabela 2. Wpływ wzrastającego zbilansowania azotu na indeks produkcyjności brutto azotu nawozowego, kg CU kg^{-1} N

Crops Rośliny	Treatments Warianty				
	NP	NPK	NPK +1MgS	NPK +2MgS	NPK +3MgS
Maize, Kukurydza	51.1[a]	52.7 [ab]	56.2 [ab]	53.6 [ab]	61.2 [b]
Spring barley Jęczmień jary	37.6 [a]	38.7 [a]	39.7 [a]	40.2 [a]	40.5 [a]
Winter oil-seed rape Rzepak ozimy	37.2 [b]	43.6 [b]	45.0 [b]	45.9 [b]	47.8 [b]
Winter wheat Pszenica ozima	39.0 [a]	43.0 [a]	45.9 [a]	45.9 [a]	47.7 [a]

[a] means following the same letter were not significantly different at α=0,05
[a] średnie oznaczone tą samą literą nie różniły się istotnie na poziomie α=0,05

Table 3. Effect of increasing N balancing on agronomic efficiency of fertilizer nitrogen, kg AE_N kg^{-1} N
Tabela 3. Wpływ wzrastającego zbilansowania azotu na efektywność netto azotu nawozowego, kg AE_N kg^{-1} N

Crops, Rośliny	Treatments, Warianty				
	NP	NPK	NPK +1MgS	NPK +2MgS	NPK +3MgS
Maize, Kukurydza	15.9 [a]	17.6 [ab]	18.5 [ab]	21.1 [ab]	26.1[b]
Spring barley Jęczmień jary	15.5 [a]	16.6 [a]	17.6 [a]	18.0 [a]	18.4 [a]
Winter oil-seed rape, Rzepak ozimy	13.9 [a]	20.3 [ab]	21.8 [ab]	22.6 [ab]	24.4 [b]
Winter wheat Pszenica ozima	15.5 [a]	19.4 [a]	22.4 [a]	22.4 [a]	24.2 [a]

[a] means following the same letter were not significantly different at α=0,05
[a] średnie oznaczone tą samą literą nie różniły się istotnie na poziomie α=0,05

Yield forming components

There has been analyzed two yields forming components of yield structure: i) kernel (grain) number per plant (KNP) and ii) thousand grain weight (TGW), assuming their response to balanced effect of MgS fertilizers. The first one, KNP, established as a rule earlier throughout grain crops growth season, responded significantly, irrespectively of the tested crop, to the applied fertilizers as compared to the control treatment (Table 4).

Table 4. Statistical evaluation of yield forming elements, kernel number per plant, KNP
Tabela 4. Ocena statystyczna wpływu nawożenia na elementy struktury plonu, KNP liczba ziarniaków w kłosie

Crops, Rośliny	Statistics, Statystyki	Control, Kont-rola	NP	NPK	NPK +1MgS	NPK +2MgS	NPK +3MgS
Maize,	mean, śred.	215.4[a]	310.6[b]	313.8[b]	321.5[b]	313.7[b]	337.4[b]
Kukurydza	SD	19.6	57.1	28.8	18.8	24.6	12.7
	CV, %	9.1	18.4	9.2	5.8	7.9	3.8
Spring barley	mean, śred.	8.3[a]	12.9[ab]	12.4[ab]	13.9[b]	14.0[b]	15.9[b]
Jęczmień j.	SD	1.5	0.8	2.0	1.9	3.1	1.0
	CV, %	18.6	6.2	15.7	13.9	22.3	6.5
Winter wheat	mean, śred.	16.3[a]	28.2[b]	30.1[b]	32.3[b]	32.6[b]	35.0[b]
Pszenica oz.	SD	3.0	5.0	2.3	2.4	4.9	3.6
	CV, %	18.4	17.7	7.6	7.4	15.0	9.8

[a] means following the same letter were not significantly different at α=0,05
[a] średnie oznaczone tą samą literą nie różniły się istotnie na poziomie α=0,05

The found differences, occurring between fertilizing treatments, were at the same level of significance. In spite of negligible statistical differences crops fertilized with Mg+S at the level of 3MgS increased in comparison to the NP treatment number of kernels (grain) by: 9% for maize; 23% for barley and 24% for winter wheat. The importance of these differences for final yield of grain (GY) are presented below:

1. Maize: $GY = 0.032KNP – 1.293$; $R^2 = 0,96^{***}$; n=6
2. Barley: $GY = -0.038KNP^2 + 1.162KNP - 4,765$; $R^2 = 0,99^{***}$; n=6
3. Wheat: $GY = 0,202KNP + 0.262$; $R^2 = 0,99^{***}$; n=6

The second yield forming component, TGW, did not show any significant response to the applied fertilizing treatments (Table 5). There has been, however, found a positive correlation with final yields of grain (GY) for winter wheat as presented by the developed equation:

$$GY = -2.725TGW^2 + 193.1TGW – 3414; R^2 = 0,96^{***}; n=6$$

The found significant response of KNP to the studied fertilizing treatments, aimed at balancing N input, shows that under studied conditions the main critical period for yield formation took place from the stage of ear growth (BBCH51) up to the beginning of kernel (grain) growth (BBCH71). The obtained results indirectly corroborate the thesis about primary importance of this particular growth period of cereal crop for final grain yield (D’Andrea et al., 2008; Otequi and Bonhomme, 1998). The found results are as a rule attributed to potassium and chloride supply in potassium fertilizers (Cakmak, 2005). However, effect of potassium as assessed by KNP increase on the NPK plot in comparison to NP one was much smaller than that occurring between NPK and NPK+3MgS treatments. Therefore, the major yield forming effect, corraborated by the found level of NUE indices increase, was significantly attributed to magnesium and sulfur. Unfortunately, there are only a few research reports considering this problem. Salvagotti and Miralles (2008) describes the effect of sulfur on development of structural elements of wheat grain yield. This author found that wheat plants well supplied with sulfur increased number of spikes and in turn unit nitrogen fertilizer productivity by 51%. Significant increase of the number of kernels per an ear of spring barley in response to elementary sulfur has been documented by Przygocka-Cyna and Grzebisz (2006). Barłóg and Frąckowiak (2008) showed that interaction of potassium and Kieserite can reveal only in favorable growth conditions for maize crop, enabling to significantly raise maize grain yield.

Table 5. Statistical evaluation of yield forming elements, thousand grain weight, TGW, g
Tabela 5. Ocena statystyczna wpływu nawożenia na elementy struktury plonu, masa tysiąca ziarniaków w g

Crops, Rośliny	Statistics, Statystyki	Control, Kont-rola	NP	NPK	NPK +1MgS	NPK +2MgS	NPK +3MgS
Maize,	mean, śred.	324.4	317.1	332.2	330.6	330.8	335.8
Kukurydza	SD	15.5	11.6	14.1	17.2	18.7	10.9
	CV, %	4.8	3.6	4.3	5.2	5.7	3.2
Spring barley	mean, śred.	43.6	43.1	44.0	43.0	42.7	41.3
Jęczmień j.	SD	0.8	0.5	1.4	1.4	3.3	0.5
	CV, %	1.9	5.7	0.9	3.1	5.9	6.7
Winter wheat	mean, śred.	36.6	36.0	35.0	35.1	35.0	35.8
Pszenica oz.	SD	0.5	2,0	0.3	1.1	2.1	2.4
	CV, %	1.5	5.7	0.9	3.1	5.9	6.7

Soil nutrient balance and yield development

The main objective of any current fertilization program is, firstly, to reach and secondly, to sustain the soil fertility at optimum level for the most sensitive crop in the given rotation. In the studied crop rotation course, maize and oil-seed rape were considered as the most sensitive crops to P and K soil fertility. Therefore, amounts of applied nutrients were established at levels oriented on nutrient requirements of these two crops. The assessment of the applied rates accuracy was conducted at the end of the studied rotation (Table 6). Soil reaction showed for the whole period a dramatic decrease from pH of 5.6 to pH of 4.3, indicating an urgent necessity of lime application. The conducted simple balance of plant available phosphorus, potassium and magnesium showed a positive effect only for potassium, which net balance amounted to 43 mg kg K_2O kg soil^{-1}. In two other cases, referring to phosphorus and magnesium, there have been found a slight drop, but dependent on the treatment. For phosphorus and magnesium a negative balance was noted for all treatments, except the NPK and NPK+2MgS, respectively.

Table 6. Soil pH and content of available nutrients before and at the end of the four-year rotation
Tabela 6. Odczyn gleby i zawartość składników przyswajalnych przed i po zakończeniu czteroletniego zmianowania

Treatments Warianty	pH	P_2O_5	K_2O $mg \cdot kg^{-1}$	Mg
Before experiment, Przed rozpoczęciem doświadczenia				
	5,6	184	186	62
At the end of four-year rotation, Po zakończeniu doświadczenia				
Control, Kontrola	4.7	168	223	50
NP	4.6	182	247	52
NPK	4.5	185	254	53
NPK+1MgS	4.3	172	220	55
NPK+2MgS	4.5	173	219	64
NPK+3MgS	4.4	169	209	59

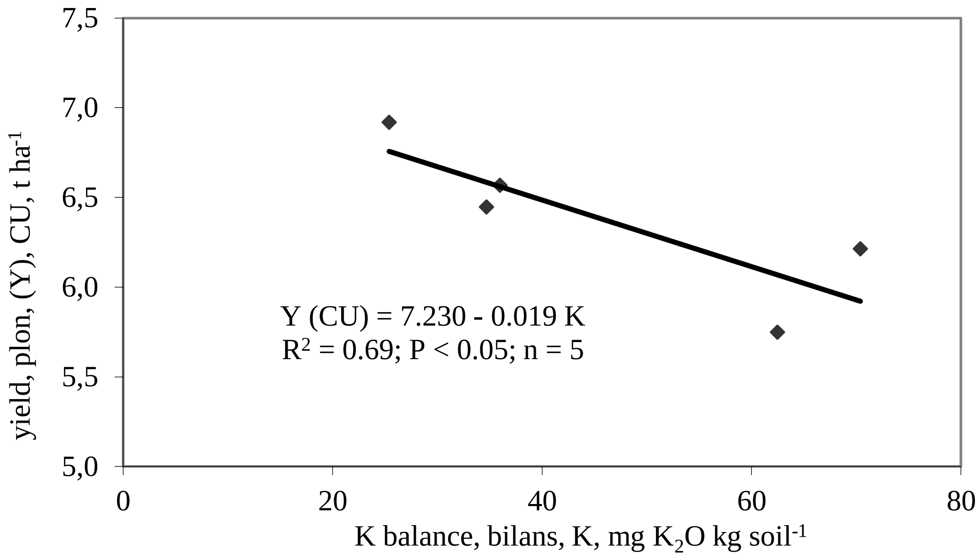

Figure 2. Response of averaged yield of crops grown in four-year rotation to balance of available potassium
Rycina 2. Zależność między średnim plonem uprawianych roślin a wartościami salda bilansu przyswajalnego potasu w glebie

In order to asses an accuracy of the applied nutrient rates, the final soil nutrient balance was regressed against an average yield for given treatment, measured in cereal units (CU). In the case of potassium, it has been found a negative trend occurring between its net balance and grain yield (Figure 2). The found relationship clearly indicates that there was a surplus of available potassium, in turn indicating also the necessity of its balancing. The second nutrient, phosphorus showed almost the same trend as found for potassium (Figure 3). However, the found yield drop follows negative balance of soil available P content, i.e. indicating also surplus of this nutrient. Quite different trend has been found for magnesium (Figure 4). The optimum balance of available nutrient for reaching the maximum yield has occurred, when its net balance was slightly below zero. In the light of the major nutrients, such as phosphorus and potassium, response to the tested fertilizing programs it can be formulated a thesis about the necessity of their further balancing by magnesium (Mg + S) external supply.

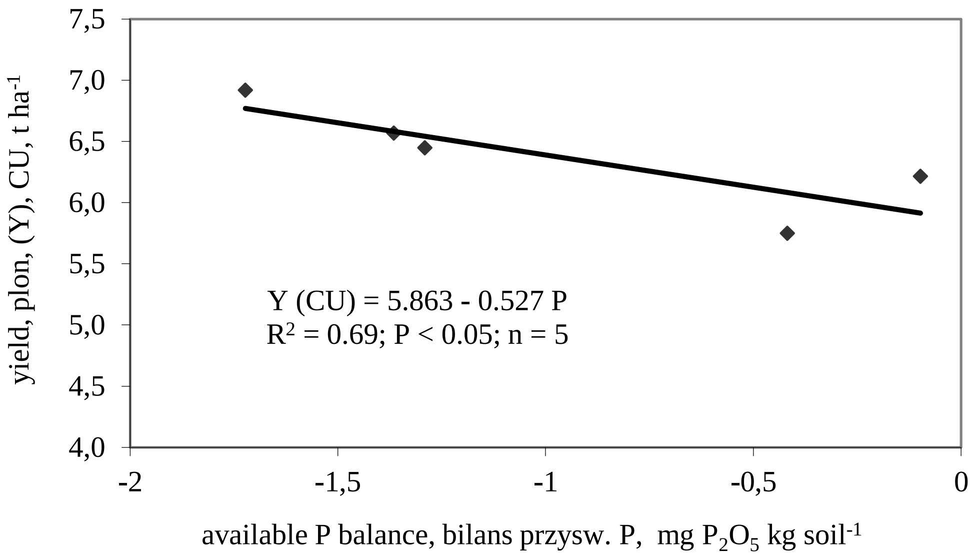

Figure 3. Response of averaged yield of crops grown in four-year rotation to balance of available phosphorus
Rycina 3. Zależność między średnim plonem uprawianych roślin a wartościami salda bilansu przyswajalnego fosforu w glebie

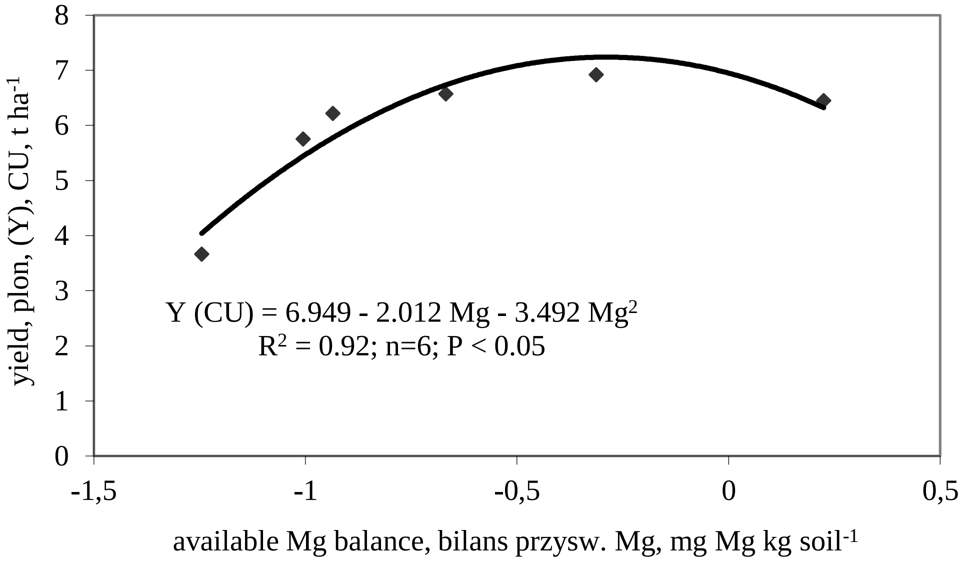

Figure 4. Response of averaged yield of crops grown in four-year rotation to balance of available magnesium
Rycina 4. Zależność między średnim plonem uprawianych roślin a wartościami salda bilansu przyswajalnego magnezu w glebie

Conclusions

- The balanced nitrogen fertilization exerted a significantly higher and positive effect on maize and oilseed rape productivity (yield) as compared to winter wheat and spring barley.
- The greatest yield increase and efficiency of nitrogen assessed by PFP_N and AE_N indices were obtained in the treatment, where potassium has been applied along with the highest rate of magnesium and sulphur (NPK+3MgS treatment).
- Kernel (grains) number per plant was a more sensitive component of yield structure response to balanced supply of basic nutrients than thousand grains weight.
- The net balance of plant available potassium and phosphorus in soil showed that their net surplus with respect to yield response was negative, in turn indicating on magnesium as a nutrient required to reach nutritional balance of N, P, K in high-yielding crops.

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