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INDICES OF TOTAL AND UNIT NUTRIENT UPTAKE BY HIGH-YIELDING WINTER OILSEED RAPE UNDER CONDITIONS OF INSTENSIVE MAGNESIUM FERTILIZATION

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Abstract. Between 2008–2010, a series of field experiments with winter oilseed rape (WOSR) were carried out on the NPK treated plot, to assess the effect of the manner of magnesium sulfate application on total and unit uptake of selected nutrients. The studies clearly showed that the supply of potassium (K) to oilseed rape is a key element in the strategy of effective nitrogen management (N).The obtained UNU and UKU indices plainly demonstrated, that an effective exploitation of WOSR yielding potential requires a relatively moderate level of N supply (in the range of 50–55 kg N·t^{-1}), provided there is also a good supply of K (in the range of 90–100 kg·t^{-1}). The highest seed yield was obtained in the year (2008), in which the ratio of total and unit K/N uptake reached 2.0. It can, therefore, be concluded that any narrower ratio of N/K, resulting from the imbalance of the applied fertilization system and/or unfavorable weather conditions, leads to the yield of WOSR decline. Data on total and unit Mg uptake clearly indicate, that magnesium sulfate is an important nutrient, which optimizes WOSR yields under moderate and deep stress growing conditions. An effective WOSR production requires an optimization of calcium and micronutrient management. The UCaU value, amounting to approximately 60 kg·t^{-1}, showed the highest WOSR productivity. The excessive values of both, total and unit uptake indices as obtained for Ca, Mn and Cu, can be considered as indicators of unfavorable growth conditions for WOSR.

Key words: magnesium sulfate, macronutrients, micronutrients, seed yield, harvest

INTRODUCTION

Winter oilseed rape (WOSR) is the leading oil crop in Poland [Kapusta 2015]. Its yielding potential is high, but the actual harvested yields are both much lower and, at the same time, highly sensitive to the course of weather in the growing season. In Europe, in recent years, yields of this crop have shown stagnation, irrespective of the region [FAOSTAT 2017]. In Poland, harvested yields rarely reach 60% of the yielding potential of currently grown varieties [COBORU 2017, GUS 2017]. There are numerous reasons for low yields in Poland. The set of most important factors responsible for insufficient exploitation of WOSR yielding potential is as follows: i) low natural fertility of arable soils, ii) prevalence of acid soil, iii) high frequency of droughts during the spring vegetation, iv) imbalanced application of main nutrients [Grzebisz 2011].

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WOSR is a crop with extremely high requirements for numerous nutrients. Unfortunately, both researchers and farmers focus their attention, mainly on nitrogen. In fact, this nutrient is the key factor responsible for the rate of plant growth and yield [Sieling and Kage 2010]. In Poland, due to highly variable soil and climate conditions, particular attention should be paid to such important nutrients as potassium (K) and magnesium (Mg). Potassium is responsible for numerous plant functions. The most important is management of water and N uptake, which have a decisive influence on the final yield of seeds. The study by Grzebisz et al. [2018] clearly documented, that plants well supplied with K during the pre-flowering period of growth produce more pods per unit area. Studies by Barłóg et al [2004] showed that K is taken up by WOSR plants in amounts exceeding nitrogen. This element requires a special attention by farmers, because the share of arable soils in Poland, poor in available potassium, exceeds 60% [GUS 2017]. Magnesium is required by plants in much lower amounts compared with N and K, but it is a key nutrient governing both N and water management [Grzebisz 2013]. Szczepaniak et al. [2016] showed, that shortage of Mg during the booting stage of WOSR growth results in the seed yield decline. Soils in Poland are naturally poor in magnesium and the share of soil with insufficient content of available magnesium is about 33% [GUS 2017].

The evaluation of currently grown crop needs for a given nutrient requires detailed sets of data on its total uptake. The total uptake of nutrients is frequently limited only to their removal in seeds [Chwil 2016]. The basis for a calculation of the nutrient requirement by the crops is an index, termed as the unit nutrient uptake (UNU). It describes the quantity of a given nutrient accumulation by 1.0 t of seeds and its respective amount in crop residues (straw + threshed pods). In spite of a strong breeding progress, resulting in new, high-yielding varieties, the existing data on UNU was developed for moderately yielding crops [Grzebisz 2011]. The modern generations of WOSR varieties show a much faster growth, which is concomitant with increasing nitrogen use efficiency, as the prerequisite of higher yield [Stahl et al. 2016]. As a result, new varieties are extremely sensitive to the growing conditions responsible for the rate of nutrient uptake.

The objective of the work is to evaluate indices of the total and the unit nutrient uptake for eight elements such as nitrogen, phosphorus, potassium, calcium, magnesium, manganese, zinc and copper, based on data from the high-yielding experiment with winter oilseed rape.

MATERIALS AND METHODS

Studies on total nutrient uptake by high yielding WOSR were carried out during the 2007/2008, 2008/2009, and 2009/2010 seasons in Donatowo (52°04′ N, 16°51′ E), Poland. The field experiment was set up on soil comprising loamy sand over sandy loam, classified as Albic Luvisol. Data on the content of available nutrients, including mineral nitrogen, are shown in Table 1. Precipitations, in spite of being year to year, were, except 2010, suitable for the studied crop.

Table 1. Agrochemical characteristics of the soil in the research plots

Year	pH (1 M KCl)	Content of nutrients, $mg \cdot kg^{-1}$ soil						N_{min} [3] ($kg \cdot ha^{-1}$)
		P[1]	rating	K[1]	rating	Mg[2]	rating	
2008	6.36	96.3	very high	151.1	high	45	medium	65.6
2009	6.55	89.1	very high	164.3	high	52	high	74.8
2010	5.96	68.4	high	103.8	medium	75	very high	68.0

[1]according to the Egner-Riehm standard procedure; [2]according to the Schachtschabel standard procedure; [3]0.01 $CaCl_2$ solution

Table 2. Experimental design: composition, rates and timing of fertilization treatments

Code of the treatment	Fertilizing treatments	N		P	K		Mg		S	
		time and rate of applied fertilizer, kg·ha^{-1}								
		A[3]	S[4]	A	A	S	A	S	A	S
C	Control	0	0	0	0	0	0	0	0	0
NP	NP[1]	27	187	30.1	0	0	0	0	0	0
NPK	NP + K	27	187	30.1	149.4	0	0	0	0	0
NPKMgS1	NPK + MgS1[2]	27	187	30.1	99.6	49.8	0	5.4	0	6.0
NPKMgS2	NPK + MgS2	27	187	30.1	149.4	0	16.2	0	18.0	0
NPKMgS3	NPK + MgS3	27	187	30.1	99.6	49.8	10.8	5.4	12.0	6.0

[1] di-ammonium phosphate, [2]Kieserite, [3]Autumn, [4]Spring
C = control; NP = nitrogen + phosphorus fertilizers; NPK = NP + potassium fertilizer; NPK + MgS1 = NPK + $^1/_3$ of the total MgS rate, spring applied; NPK + MgS2 = the total rate of 16.2 kg Mg and 18 kg S·ha^{-1}; autumn applied; NPK + MgS3 ($^2/_3$ of the total MgS rate – autumn, $^1/_3$ – spring applied

A source of data was a field trial consisting of six treatments, arranged in a randomized complete block, and replicated four times. The details are shown in Table 2. Phosphorus in the total amount of 30.1 kg P·ha^{-1} (di-ammonium phosphate, 18% N, 46% P_2O_5), and K in the amount of 149.4 kg K·ha^{-1} (muriate of potash [60% K_2O) and/or Korn-Kali (40% K_2O, 6% MgO, 4% Na_2O and 12% SO_3) was applied each year before sowing. Magnesium sulfate was applied in accordance to the experiment design in the form of Korn-Kali and/or Kieserite. The total rate of N was 207 kg·ha^{-1} (ammonium saltpeter, 34.0% N), in which 27 kg N·ha^{-1} were applied before WOSR sowing and remaining part in spring each season (102 kg N·ha^{-1} before spring regrowth and 78 kg·ha^{-1} at BBCH 30). The Chagall variety of WOSR was sown at the end of August and harvested by a plot combine harvester at the end of July from an area of 15 m^2. The seeds were harvested at maturity when the moisture content was 8% dry weight.

Plant material used in determination of dry matter, and nutrient concentration was collected from an area of 1.0 m^2 at BBCH 89. Nitrogen concentrations were determined using a standard macro-Kjeldahl procedure, with accuracy of 0.1 mg N. The plant materials for the elements determination were mineralized at 600°C. The obtained ash was then dissolved in 33% HNO_3. The phosphorus concentration was measured by the vanadium-molybdenum method using a Specord 2XX/40 at a wavelength of 436 nm. The content of K, Mg and Ca, Mn, Zn, and Cu was determined using a FAAS.

The amount of given nutrients, accumulated in the total WOSR biomass at BBCH 89 was calculated by multiplying its concentration and its biomass for specific plant parts. The detailed information on the concentration of the studied nutrients in seeds was described by Szczepaniak et al. [2017]. Data on their concentration in straw are available from the Authors.

The index termed as UNU was calculated based on the following formula:

$$UNU = N_T/Y$$

where:

UNU – unit uptake of a given nutrient, kg or g•t^{-1} seeds + respective amount in crop residues,

N_T – total uptake of a given nutrient (seed + straw), kg, g•ha^{-1},

Y – yield of seeds, t•ha^{-1}.

The data were subjected to conventional analysis of variance using STATISTICA® 10 (StatSoft, Krakow, Poland). The differences between treatments were evaluated with Tukey's test. In tables, figures, and developed equations, the results from the F test (***, **, *) indicate significance at the $P < 0.001$, 0.01, and 0.05, respectively. In the second step of the diagnostic procedure, stepwise regression was applied to define an optimal set of variables for a given crop characteristic. In the computational procedure, a consecutive variable was removed from the multiple linear regressions in a step-by-step manner. The best regression model was chosen based on the highest F-value for the model and significance of all independent variables.

RESULTS AND DISCUSSION

The seed yield of WOSR was significantly driven by an interaction of experimental factors with years (Table 3). The highest yield, reaching 5.8 $t \cdot ha^{-1}$, was obtained in 2008 on the plot fertilized with NPK plus magnesium sulfate applied in the full rate in autumn (MgS2). In 2009, the average yield was significantly lower. The highest, reaching 5.1 $t \cdot ha^{-1}$, was obtained from the plot fertilized only with NPK. In 2010, the average yield was by 34% lower with respect to 2008, and by 28% compared to 2009. The highest, harvested on the plot with magnesium applied in full rate in autumn (MgS2), amounted to 3,5 $t \cdot ha^{-1}$. This study clearly indicated, that in good growth conditions, assured by the adequate soil fertility level and the favorable course of weather, the application of magnesium sulfate in autumn resulted in extremely high yields. In good 2008, the applied MgS in autumn was the key reason for the seed yield increase by 1.0 $t \cdot ha^{-1}$ compared to NPK treatment. In the unfavorable 2010, the same manner of MgS application resulted in the yield increase by 0.4$t \cdot ha^{-1}$.

The total nutrient uptake by WOSR was year-to-year variable (Table 3). All studied elements showed a significant response to the tested treatments and, except zinc, to the course of weather. The crucial sets of elements for the final yield of seed were data on N and K uptake. The stepwise regression clearly showed, that the observed yield variability of total uptake of both elements was decisive for the yield of seeds (Y):

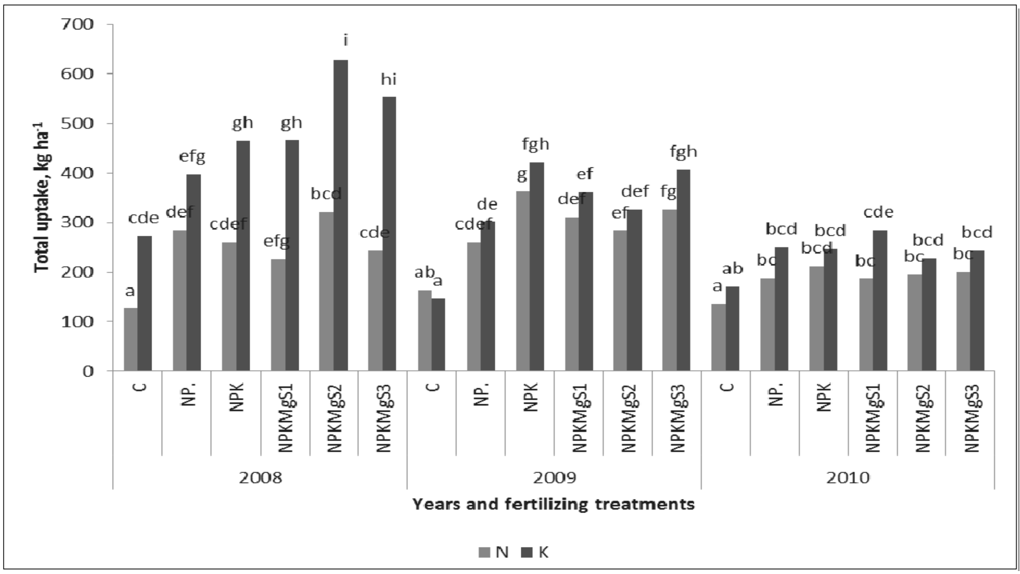
$$Y = 1147 + 5.17N + 4.77K \text{ for } n = 72 \text{ and } R^2 = 0.85.$$

The total uptake of N, averaged over other treatments, reached the highest value in 2009, which amounted to 363 $kg \cdot ha^{-1}$ on the NPK plot (Fig. 1). It was by 102 $kg \cdot ha^{-1}$ higher compared to the NP plot and by 79 $kg \cdot ha^{-1}$ with respect to the MgS2 one. For comparison, yield of seeds were 5.1, 3.9 and 4.4, respectively. In 2008, the average total N uptake was significantly lower, and amounting at the highest to 322, was the attribute of the MgS2 plot. It was by 60 $kg \cdot ha^{-1}$ higher compared with the NPK plot, and by 38 kg ha^{-1} higher with respect to the NP one. At the same time, the seed yields were 5.8, 4.9 and 4.6 $t \cdot ha^{-1}$. These two sets of data clearly indicate 2008 as the year favorable for exploitation of WOSR yielding potential. In 2010, the average total N uptake was significantly lower compared with the first two growing seasons. The highest N uptake of 213 $kg \cdot ha^{-1}$ was the attribute of the NPK plot, but the highest yield was harvested on the MgS2 plot with N uptake lower by 17 kg $N \cdot ha^{-1}$. These sets of data clearly stress the impact of applied magnesium sulfate on N uptake by WOSR. The application of MgS exerted a positive impact on yield in 2008 and 2010, but negative in 2009. The main reason for the observed disturbance was an excessive growth of vegetative organs in 2009, which in turn delayed the development of yield components [Szczepaniak 2015]. These data clearly support the hypothesis on the significant impact of magnesium sulfate on N management, but its yielding effect depends on the course of weather [Grzebisz 2013].

Table 3. Total uptake of nutrients by high yielding oilseed rape

Treatment	Level of treatment	N	P	K	Mg	Ca	Zn	Mn	Cu	Yield ($kg \cdot ha^{-1}$)
		$kg \cdot ha^{-1}$					$g \cdot ha^{-1}$			
Year (Y)	2008	244 b	58 b	464 c	31 c	259 c	219 a	379 a	55	4750 c
	2009	285 c	42 a	328 b	23 b	142 c	508 b	515 c	50	4252 b
	2010	187 a	58 b	238 a	20 a	207 b	254 a	481 b	52	3045 a
Fertilizing[1] (F)	C	142 a	36 a	197 a	18 a	158 a	225 a	249 a	38 a	2881 a
	NP	245 b	50 ab	317 b	24 b	196 b	308 b	431 b	51 b	3814 b
	NPK	279 b	60 b	378 bc	28 b	223 b	377 c	531 cd	58 b	4359 ab
	NPKMgS1	241 b	52 ab	371 bc	26 b	196 b	356 bc	464 bc	52 b	4097 ab
	NPKMgS2	267 b	59 ab	394 c	26 b	223 b	334 bc	478 bc	57 b	4550 c
	NPKMgS3	257 b	58 ab	401 c	27 b	220 b	364 bc	594 d	57 b	4391 ab
Source of variation										
Year		***	***	***	***	***	***	***	n.s.	***
Fertilizing		***	***	***	***	***	***	***	***	***
Year x Fertilizing		**	**	***	**	***	n.s.	***	**	*

[1]description as in Table 2
***, **, * significant at $p < 0.001$, $p < 0.01$, and at $p < 0.05$; n.s. – not significant
The same letter indicates a lack of significant differences within the treatment

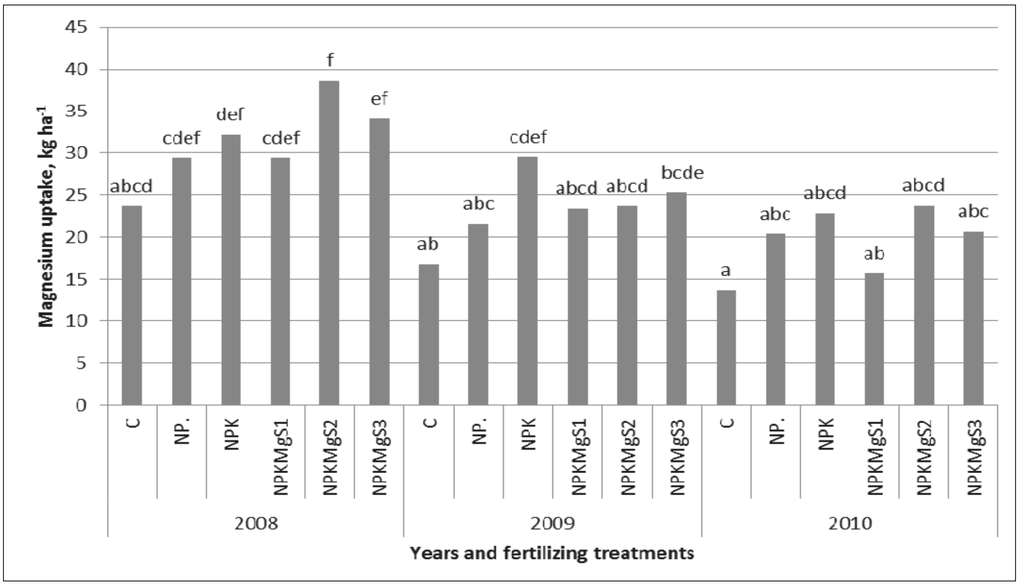


Legend: N, K – nitrogen and potassium, respectively; C = control; NP = nitrogen + phosphorus fertilizers; NPK = NP + potassium fertilizer; NPK + MgS1 = NPK + 1/3 of the total MgS rate, spring applied; NPK + MgS2 = the total rate of 16.2 kg Mg and 18 kg S ha-1; autumn applied; NPK + MgS3 (2/3 of the total MgS rate - autumn, 1/3 – spring applied
[a]the same letter indicates a lack of significant differences within the treatment

Fig. 1. Total uptake of nitrogen and potassium by winter oilseed rape as affected by fertilizing treatments in consecutive years

The total K uptake by WOSR was, in all years, significantly higher compared to N (Fig. 1). In 2008, the highest K uptake of 628 kg•ha^{-1} was the attribute of the MgS2 plot. It was by 163 and by 230 kg•ha^{-1} higher, compared to NPK and NP plots, respectively. The same trend was observed for the seed yield. The K/N ratio for these three treatments was 2.0, 1.8, and 1.4, respectively. In 2009, the maximum K uptake, amounting to 422 kg•ha^{-1}, was the attribute of the NPK plot. It was higher by 95 kg with respect to the MgS2 plot, and by 120 kg•ha^{-1} compared to the NP one. The K/N ratio was, irrespective of the treatment, 1.2:1, i.e. much narrower compared to those recorded in 2008. In 2010, the highest K uptake of 285 was the attribute of the MgS1 plot. It was by 57 kg•ha^{-1} higher compared to the MgS2 plot. The K/N ratio was slightly wider (1.5:1 versus 1.2:1), but the seed yield was by 0.2 t•ha^{-1} lower with respect to the MgS2 plot. In general, the highest yield of seed was recorded in the year with the K/N ratio of total uptake of both nutrients, excluding the absolute control, around 2.0. It can be, therefore, concluded that any narrower ratio of this index, resulting from both weather and the imbalance fertilizing, leads to yield depression. This study clearly showed, that potassium supply to WOSR plant is a crucial component for an effective management of applied nitrogen.

The impact of the total magnesium uptake on the yield of seeds was a significant, but not a decisive factor, as recorded for N and K (Table 3 and 4). The total amount of Mg accumulated in WOSR biomass at harvest declined in the following order: 2008 > 2009 > 2010. The advantage of 2008 over the other two was observed for all treatments (Fig. 2). The amount of Mg taken up by plants grown on the absolute control clearly stresses the importance of soil fertility level. In

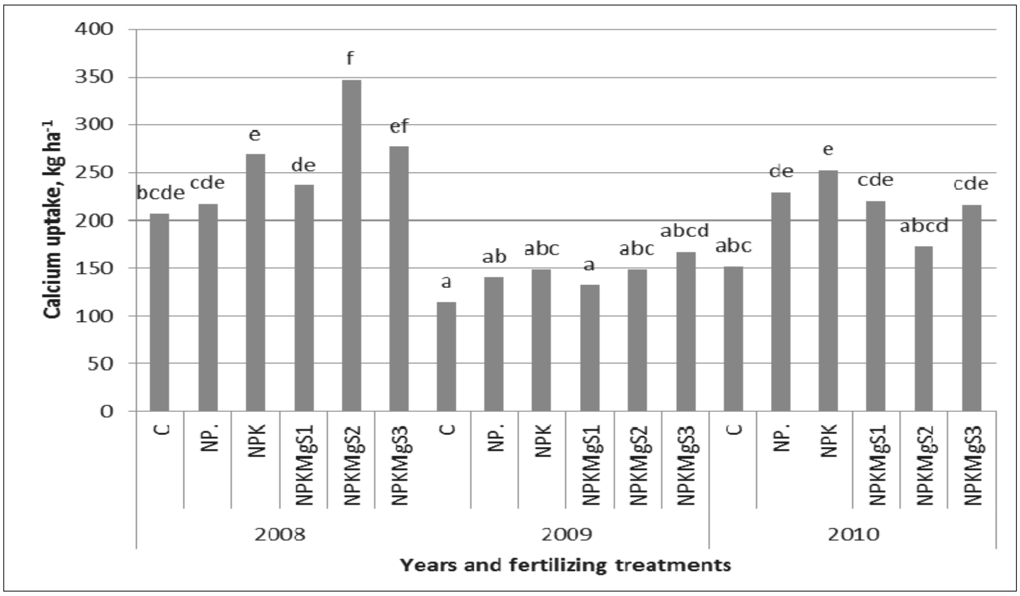


Legend: as described in Fig. 1
[a]the same letter indicates a lack of significant differences within the treatment

Fig. 2. Total uptake of magnesium by winter oilseed rape as affected by fertilizing treatments in consecutive years

2008, WOSR plants took 24, whereas in 2009, and 2010 only 17 and 14 kg•ha^{-1}, respectively. This difference was even more striking on the MgS2 plot and amounted to 39, 24, and 24 kg•ha^{-1} for 2008, 2009, and 2010, correspondingly. The total amount of accumulated Mg was significantly and, at the same time, positively correlated with the total uptake of K, followed by N, Ca and P (Table 4). These dependencies corroborate the opinion by Grzebisz [2013], that magnesium supply to high-yielding crops should be precisely balanced with other nutrients, especially with nitrogen and potassium. Any shortage or excess of MgS led to yield decline. In spite of significant impact on the yield, its supply was in shortage in favorable 2008 and unfavorable 2010, but in excess in the wet 2009.

The other five nutrients, in spite of their positive impact on the yield, were less significant. It means, that their supply to WOSR plants was more or less at a sufficient level with respect to the harvested yield (Table 3 and 4). The total uptake of phosphorus (P) showed much minor year-to-year variability compared to the leading elements. It was significantly lower in 2009 compared to the other two years. The impact of experimental treatments was most striking for NPK, for which, the total P uptake was higher by 20% compared to NP plot. Almost the same trend was observed for calcium (Ca; Fig. 3). This nutrient requires more attention, because it is frequently omitted in fertilizing schedules by WOSR producers. Plants grown in 2008 on the top-yielding plot, i.e. MgS2 accumulated at harvest 348 kg•ha^{-1} of Ca. It was by 79 kg•ha^{-1} higher compared to the NPK plot, which yielded by 1,0 t•ha^{-1} lower. In 2009, the top Ca uptake, amounting only to 149 kg•ha^{-1}, was the attribute of the NPK plot. The same value was recorded for the MgS2 one. In 2010, plants grown on the NPK plot took up 252 kg•ha^{-1}, whereas on the MgS2 only



Legend: as described in Fig. 1
[a]the same letter indicates a lack of significant differences within the treatment

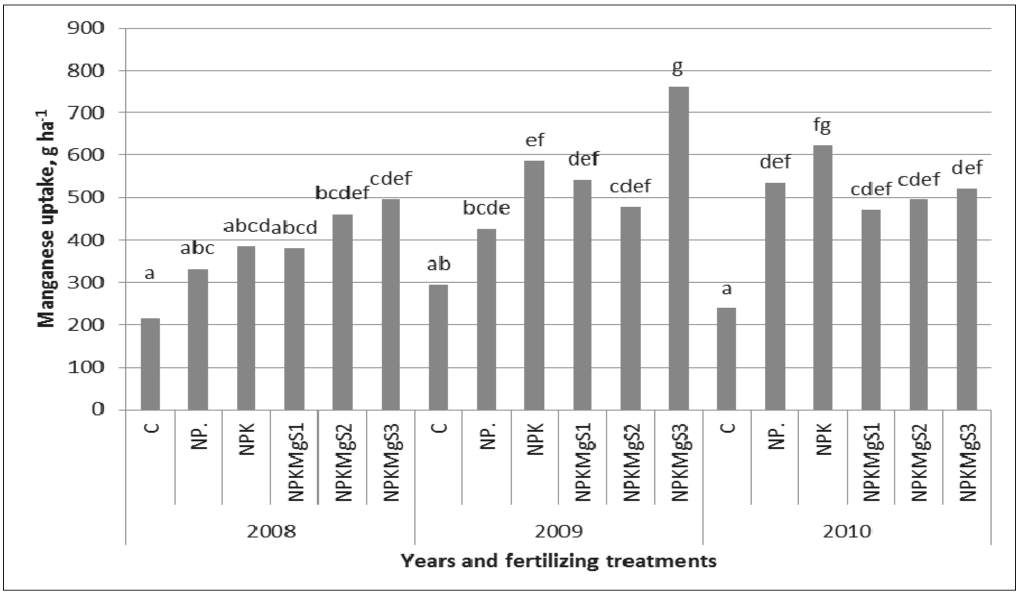
Fig. 3. Total uptake of calcium by winter oilseed rape as affected by fertilizing treatments in consecutive years

221 kg•ha^{-1} of Ca. The positive relationship between Mg and Ca is transparent in all years, but the strongest was in 2009. In this particular year, the supply of both elements to WOSR plants was insufficient to take Mg under control (Table 4). The set of data for 2010 (Ca uptake, yield) closely corresponds to data presented by Podleśna [2004].

Table 4. Correlation matrix of total nutrient uptake and seed yield

	P	K	Mg	Ca	Zn	Mn	Cu	Yield
N	0.30*	0.67***	0.61***	0.13	0.66***	0.55***	0.59***	0.80***
P	1.00	0.51***	0.56***	0.75***	-0.18	0.39**	0.78***	0.41***
K		1.00	0.88***	0.62***	0.13	0.26*	0.71***	0.89***
Mg			1.00	0.68***	0.09	0.21	0.66***	0.84***
Ca				1.00	-0.43***	0.09	0.59***	0.44**
Zn					1.00	0.60***	0.19	0.35**
Mn						1.00	0.53***	0.33**
Cu							1.00	0.64***

***, **, * significant at $p < 0.001$, $p < 0.01$, and at $p < 0.05$



Legend: as described in Fig. 1

[a]the same letter indicates a lack of significant differences within the treatment

Fig. 4. Total uptake of manganese by winter oilseed rape as affected by fertilizing treatments in consecutive years

Among the studied micronutrients, only zinc (Zn) did not show year-to-year variability (Table 3). Its uptake was the highest in 2009, being twice as high compared to the other years. The highest Zn total uptake, taking into account all experimental treatments, was the attribute of the NPK plot. The total uptake of manganese (Mn) was significantly governed by interaction of trials with years (Fig. 4). It reached the highest values of 762 g•ha^{-1} for the MgS3 treatment in 2009. In 2008, it was also the highest on the MgS3 plot, amounting to 496 g·ha^{-1}, whereas in 2010 on the NPK plot (624 g•ha^{-1}). All these plots did not reach the top yields in consecutive years of study. Therefore, Mn impact on the yield was relatively low (Table 4). In contrast, the impact of copper (Cu) on the yield was more significant ($r = 0{,}64^{***}$). In spite of important interaction between experimental treatments and years, the variability between plots in total Cu uptake was low. Its total uptake for the absolute control plots ranged from 32 to 44 g•ha^{-1}, whereas between fertilized treatments from 47 to 68 g•ha^{-1}. The relationships between N total uptake and total uptake of micronutrients were positive, but relatively low (Table 4). This type of relationship indicates their shortage for high-yielding WOSR crop [Grzebisz et al. 2010].

The UNU indices for four studied nutrients responded significantly to the interaction of experimental treatments and years (Table 5). The lack of N and K indices' response to weather variability clearly shows their conservative character. For N, the UNU index ranged from 51 kg•t^{-1} in 2008 to 66 kg•t^{-1} in 2009. The same level of variability was observed between experimental treatments, indicating UNU of around 60 kg•t^{-1} as the optimum. This value is in the upper level as suggested by Finck [1992] and at the lower level as results from the study by Barłóg et al. [2004]. In addition, it did not show the relationship with the seed yield. It means that N

Table 5. Indices of unit nutrient uptake

Treatment	Level of treatment	N	P	K	Mg	Ca	Zn	Mn	Cu
		kg·t⁻¹ seeds					g·t⁻¹ seeds		
Year (Y)	2008	51 a	12 b	96 b	6.6 b	54 b	46 a	79 a	11 a
	2009	66 b	10 a	75 a	5.5 a	34 a	121 c	119 b	12 a
	2010	62 b	19 c	79 a	6.5 b	69 c	84 b	159 c	17 b
Fertilizing[1] (F)	C	51 a	13	69 a	6.3	56	81	90 a	14
	NP	64 b	14	82 ab	6.2	53	83	121 ab	14
	NPK	65 b	15	86 ab	6.6	55	88	135 b	14
	NPKMgS1	59 ab	13	90 b	6.3	50	88	117 ab	13
	NPKMgS2	59 ab	13	83 ab	5.5	48	76	111 ab	13
	NPKMgS3	59 ab	14	91 b	6.2	53	85	141 c	13
Source of variation									
Year		***	***	***	***	***	***	***	***
Fertilizing		**	n.s.	**	n.s.	n.s.	n.s.	***	n.s.
Year x Fertilizing		n.s.	n.s.	n.s.	*	***	n.s.	**	*

[1]description as in Table 2
***, **, * significant at p < 0.001, p < 0.01, and at p <0.05; n.s. – not significant
The same letter indicates a lack of significant differences within the treatment

Table 6. Matrix of correlation between unit nutrient indices and seed yield

	P	K	Mg	Ca	Zn	Mn	Cu	Yield
N	0.13	0.04	-0.06	-0.09	0.59***	0.41***	0.26*	-0.07
P	1.00	0.06	0.46***	0.81***	-0.12	0.63***	0.80***	-0.56***
K		1.00	0.30*	0.22	-0.39**	-0.14	0.05	0.44***
Mg			1.00	0.65***	-0.19	0.25*	0.33**	-0.17
Ca				1.00	-0.37**	0.41***	0.69***	-0.47***
Zn					1.00	0.46***	0.07	-0.24*
Mn						1.00	0.57***	-0.44***
Cu							1.00	-0.64***

***, **, * significant at p < 0.001, p < 0.01, and at p <0.05

supply to WOSR was in optimum and its uptake within the range of 50-55 fulfills conditions of high-yielding WOSR crop [Grzebisz, 2011]. For K, its unit uptake (UKU) varied from 75 $kg{\cdot}t^{-1}$ in 2009 to 96 $kg{\cdot}t^{-1}$ in 2008. The importance of K for the yield was corroborated by the developed stepwise model:

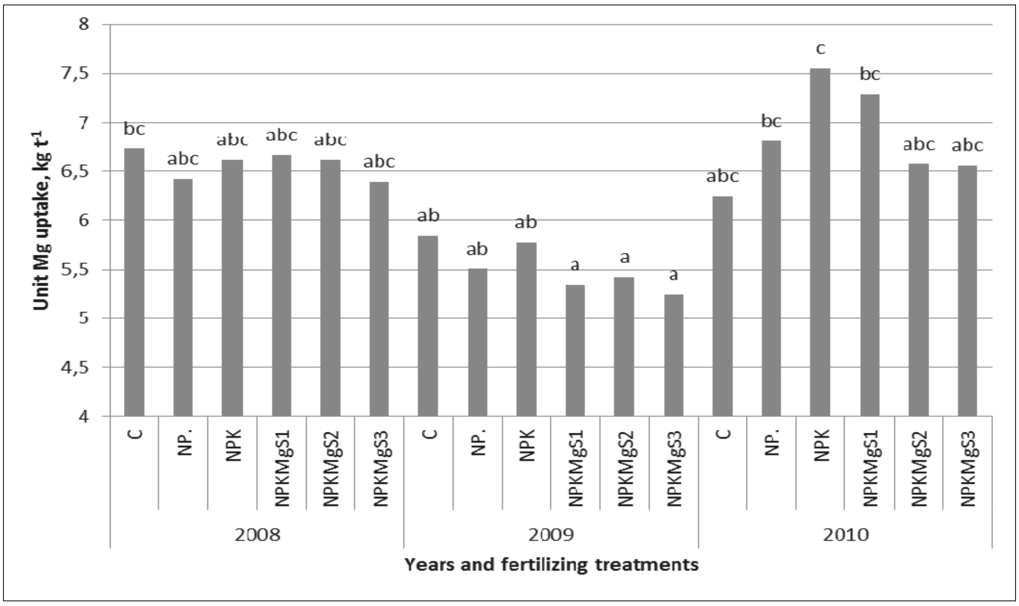
$$Y = 4613 + 27.5UKU - 214UCuU \text{ for } n = 71 \text{ and } R^2 = 0.62,$$

where:
UKU, UCuU – unit K, and Cu uptake, kg•t^{-1}, g•t^{-1}, respectively.

The optimum relationship between K and N unit indices in 2008 was 1.9:1. This relationship should be taken into account by WOSR producers during the fertilizing technology preparation. These two sets of data clearly inform that a high-yielding WOSR crop requires a relatively moderate supply of N, provided a high supply of K. This dependence is crucial for the high-yielding WOSR crop. Unfortunately, it is frequently omitted by farmers both during the K soil fertility preparation and N fertilizer application.

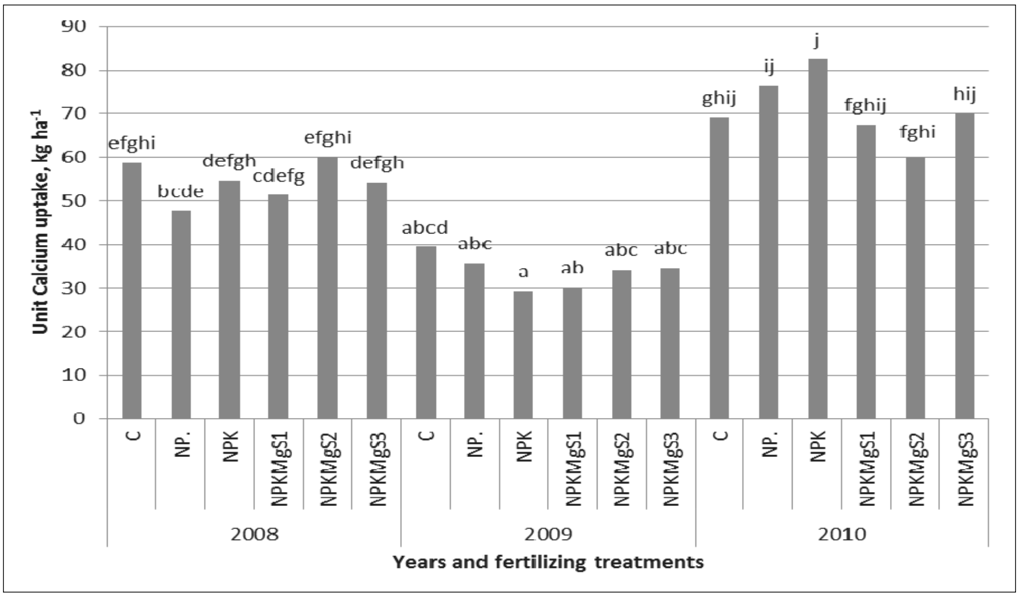
The unit phosphorus uptake (UPU) indices showed variability in response to the weather course, ranging from 10 kg•t^{-1} in 2009 to 19 kg•t^{-1} in 2010. The double value, as recorded for 2010, indicates low exploitation of P taken up by WOSR plants [Grzebisz et al. 2018]. It is necessary to stress positive relationships between UPU and Ca, Cu, and Mn indices (Table 6). All these indices were negatively correlated with the seed yield, indirectly showing their excessive uptake with respect to the harvested yield. The same, yearly induced trend was found for Zn. Its unit uptake (UZnU) in 2009 was almost 3-times, and in 2010, 2-times higher compared to 2008. At the same time, it was positively correlated with UNU, but negatively with the other indices.

The unit calcium uptake (UCaU) showed the strongest response to the interaction of experimental factors and years (Fig. 5). On average, its value in 2009 was twice as low compared to 2010. In this particular year, values above 70 kg•t^{-1} of Ca were recorded for three treatments, including NPK (83 kg•t^{-1}). In contrast, its value on the MgS2 plot with the highest yield, amounted to 60 kg•t^{-1} of Ca. The same value was recorded for the identical plot in 2008, but the seed yield was 5,8 t•ha^{-1}, versus 3,5 t•ha^{-1}. Any index value above, like in 2010 or below as in 2009, resulted in the yield decline. The index value of 60 kg•t^{-1} can be, therefore, used as a standard during a



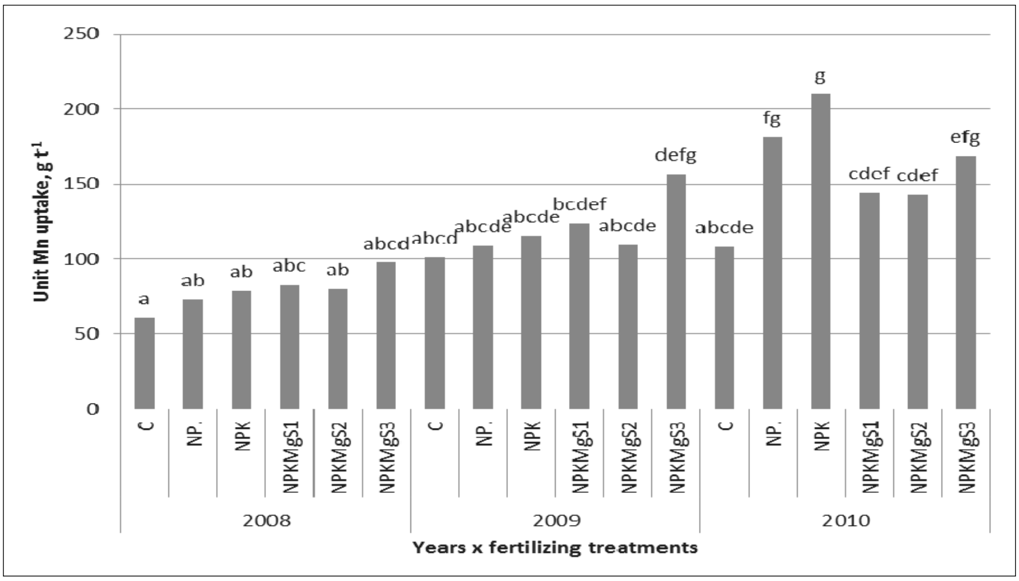
Legend: as described in Fig. 1
[a]the same letter indicates a lack of significant differences within the treatment

Fig. 5. The effect of fertilizing treatments on the unit Mg uptake by winter oilseed rape in consecutive years



Legend: as described in Fig. 1
[a]the same letter indicates a lack of significant differences within the treatment

Fig. 6. The effect of fertilizing treatments on the unit Ca uptake by winter oilseed rape in consecutive years



Legend: as described in Fig. 1
athe same letter indicates a lack of significant differences within the treatment

Fig. 7. The effect of fertilizing treatments on the unit Mn uptake by winter oilseed rape in consecutive years

preparation of fertilizing technology for WOSR crop. The negative relationship between UCaU and the seed yield stresses the excess of Ca uptake in 2010. The UCaU of 60 kg·t^{-1} is in the range published by Podleśna [2004] for the maximum Ca uptake. The unit Mg uptake (UMgU) showed very similar trends as observed for UCaU (Table 6). The index value of 6,5 kg·t^{-1} of Mg should be taken as a standard for high-yielding WOSR crops.

There are no data about UNU for micronutrients. The unit manganese uptake (UMnU) was year-to-year variable, reaching on average, the highest values in the unfavorable 2010 (Fig. 6). It was double compared to the high yielding 2008. Its value for the MgS2 plot in 2008 amounted to 80 g·t^{-1}, whereas in 2009 to 109 g·t^{-1}, and in 2010 to 143 g·t^{-1}. Almost the same trend was observed for the unit copper uptake (UCuU). Its values were significantly higher in 2010, the year of the lowest yielding (Fig. 7). In addition, the highest value was the attribute of the absolute control plot. In 2008 and 2009, the optimum UCuU index was around 12 g·t^{-1}, whereas 17 g·t^{-1} in 2010. The observed trends of UNU for Ca, Mn, and Cu can be treated as indicators of sub-optimum conditions for the growth and yielding of WOSR plants.

CONCLUSIONS

1. The exploitation of winter oilseed rape yielding potential is possible provided there is a well-balanced supply of nitrogen and potassium.
2. The highest seed yield can be achieved provided the ratio of total or unit K and N is around 2.0.
3. Any ratio of total or unit K/N uptake below 2.0 leads to the decline of oilseed rape yield.
4. The application of magnesium sulfate in autumn is the best strategy for increasing K uptake, as the prerequisite of N productivity optimization.
5. The excessive uptake of calcium, manganese and copper by oilseed rape, i.e. above threshold values for high-yielding crop, is an indicator of unfavorable growth conditions.

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WSKAŹNIKI POBRANIA CAŁKOWITEGO I JEDNOSTKOWEGO SKŁADNIKÓW POKARMOWYCH PRZEZ WYSOKO-PLONUJĄCY RZEPAK OZIMY W WARUNKACH INTENSYWNEGO NAWOŻENIA MAGNEZEM

Synopsis. W latach 2008–2010 przeprowadzono serię doświadczeń polowych z rzepakiem ozimym (WOSR) celem oceny wpływu sposobu stosowania siarczanu magnezu na tle NPK na całkowite i jednostkowe pobranie wybranych składników pokarmowych. Przeprowadzone badania wyraźnie wykazały, że dostarczanie rzepakowi potasu (K) jest kluczowym elementem strategii skutecznego zarządzania azotem (N). Uzyskane indeksy UNU i UKU wyraźnie pokazały, że efektywna eksploatacja potencjału WOSR wymaga względnie umiarkowanego poziomu zaopatrzenia w N (w zakresie 50–55 kg $N \cdot t^{-1}$), pod warunkiem dobrej podaży K (w przedziale 90–100 kg$\cdot t^{-1}$). Największy plon nasion uzyskano w roku (2008), w którym stosunek całkowitego i jednostkowego pobrania K/N osiągnął 2,0. Można, zatem stwierdzić, że jakikolwiek węższy stosunek N/K, wynikający z braku równowagi w stosowanym systemie nawożenia, czy też niekorzystnych warunków pogodowych, prowadzi do spadku plonów rzepaku. Dane dotyczące całkowitego i jednostkowego poboru Mg wyraźnie wskazują, że siarczan magnezu jest ważnym składnikiem pokarmowym, który optymalizuje wydajność WOSR w warunkach umiarkowanego i głębokiego stresu. Efektywna produkcja WOSR wymaga także optymalizacji zarządzania wapniem i mikroelementami. Wartość UCaU, wynosząca około 60 kg$\cdot t^{-1}$, wykazała największą produktywność rzepaku. Nadmierne wartości indeksów pobrania całkowitego i jednostkowego uzyskane dla Ca, Mn i Cu można uznać za wskaźniki informujące o niekorzystnych warunków wzrostu rzepaku.

Słowa kluczowe: siarczan magnezu, makroelementy, mikroelementy, plon, zbiór

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