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SULPHUR AS A FACTOR THAT AFFECTS NITROGEN EFFECTIVENESS IN SPRING RAPESEED AGROTECHNICS PART III. AGRONOMIC USE EFFICIENCY OF NITROGEN

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ABSTRACT

Background. In view of the increased interest in rapeseed cultivation that has been observed in Poland in recent years, and due to an increasing shortage of sulphur in Polish soils, a study was undertaken on the effect of nitrogen and sulphur fertilization on the uptake of those elements in the seeds of the spring rapeseed cultivar Star and on the agricultural effectiveness and utilization of nitrogen from fertilizers.
Material and methods. In a three-year-long study, experimental objects with different sulphur application methods (in-soil and foliar) and control with no nitrogen or sulphur fertilization were located on one field. Nitrogen fertilization at the doses of 0, 60, 120, and 180 kg $N \cdot ha^{-1}$ was the first factor, and sulphur fertilization at the doses of 0, 20, and 60 kg $S \cdot ha^{-1}$ was the second factor. The experiment was set up on degraded Phaeozems with a low sulphur content.
Results. In the conditions of joint nitrogen and sulphur fertilization, the nitrogen uptake in the seeds of spring rapeseed, as well as the agricultural effectiveness and the utilization of this element from the fertilizer were higher than without the sulphur application. In every growth season the combined use of nitrogen and 60 kg $S \cdot ha^{-1}$ usually made it possible to obtain the highest values of the studied parameters. Sulphur application method only to a low extent differentiated the uptake of the studied elements, agricultural effectiveness, and nitrogen utilization.
Conclusion. Supplementing spring rapeseed nitrogen fertilization with an application of sulphur affected nitrogen uptake and its effectiveness and utilization from fertilizers, which may have positive economic and environmental consequences.

Key words: *Brassica napus* L., fertilization, nitrogen uptake, oilseed crops, sulphur uptake

INTRODUCTION

Since the last decade of the 20th century, seed production of oilseed crops has been growing steadily (Bodył, 2014; FAOSTAT, 2015). This tendency is the result of an increasing demand for plant oils and for the by-product solvent cake, which is a valuable animal fodder that is especially used in countries where using meat and bone meal in fodder is banned (Dzwonkowski and Bodył, 2014). Another factor that has stimulated the increase in the production of oilseed crops is the not stable prices of crude oil, which boost the price competitiveness of biofuels (Izdebski *et al.*, 2014). Biofuels are made of methyl

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esters of higher fatty acids, the source of which is seeds of those oilseed plant species (Plichta, 2014).

In Poland, winter rapeseed has the highest proportion in the cultivation of oilseed crops. In the year 2005, rapeseed and agrimony sowing area amounted to 550 thousand ha, and had a yield of 1449.8 thousand tons (GUS, 2016). Ten years later, the data was, respectively, 951 thousand ha and 3275.8 thousand tons.

In Poland, winter rapeseed cultivars are those primarily cultivated. Spring rapeseed is of lower economic significance, since its yield is lower (the difference is 35-40%) and it is more sensitive to drought (Rudko, 2011). However, spring rapeseed also has many advantages: it is a very good forecrop for winter cereals, has 30% lower demands for fertilizers, and demonstrates lower susceptibility to pathogens than winter rapeseed, which together generate lower costs of cultivation (Mrówczyński and Pruszyński, 2008). Moreover, spring rapeseed may be the only successive crop after frozen winter rapeseed as for example in a situation where herbicides had been applied on the plantation in autumn making it impossible to introduce spring cereals. Productivity of fat from spring and winter rapeseed is similar, but the seeds of spring cultivars contain more total protein and less fibre and glucosinolates (Rudko, 2011).

Rapeseed, like other *Brassicaceae* (the cabbage family) is one of the species with high nutritional demands (50-70 kg $S \cdot ha^{-1}$) in regard to sulphur. Actions undertaken in recent decades in Poland for environmental protection have caused a decrease in the atmospheric accumulation of sulphur, which clearly limits the availability of this element for cultivated plants (Siebielec *et al.*, 2012) and intensifies the shortage of this element, particularly in rapeseed (Wielebski, 2015). Therefore, fertilization of this species with sulphur has become a necessity, which is confirmed by the studies of many authors (Zhao *et al.*, 2003; Podleśna, 2009; Barczak, 2010; Wielebski, 2011). It ought to be underscored that the need for winter rapeseed fertilization with sulphur increases in the conditions of intensive nitrogen fertilization (Podleśna, 2013; Wielebski, 2015).

In view of the increased interest in rapeseed cultivation observed in recent years in Poland and due to an increasing shortage of sulphur in Polish soils, this study was undertaken, the hypothesis of which assumed there would be a positive effect from nitrogen and sulphur fertilization, through in-soil or foliar application, on the uptake of those elements in the yield of spring rapeseed seeds and on the agricultural effectiveness of nitrogen and its utilization from fertilizers.

MATERIAL AND METHODS

The three-year-long field experiment was carried out in Kaźmierzewo in the commune of Mrocza, in the Kuyavian-Pomeranian Voivodship. It was set up on degraded Phaeozems, defective wheat complex, IIIb soil valuation class (IUSS 2015). Soil was of neutral pH, which varied from 6.5-7.1. Soil richness in the available forms of phosphorus and potassium was estimated as very high. It varied between, respectively, 101 and 108 mg $P \cdot kg^{-1}$ and 104 and 187 mg $K \cdot kg^{-1}$. Magnesium content was average (35-38 mg $Mg \cdot kg^{-1}$) and sulphur content was low (1.90-1.96 $mg \cdot kg^{-1}$). The soil had a regulated water regime.

In the experiment, plots with different dates and methods of sulphur application and control plot (with no nitrogen or sulphur fertilization) were located on one field,. The experiment was set up in a split-block design in four repetitions. The spring rapeseed cultivar Star (DLF Trifolium, Denmark) was cultivated. Under the forecrop, which consisted of sugar beet, cattle manure was applied in the amount of 30 $Mg \cdot ha^{-1}$, and after the forecrop harvest medium ploughing was carried out (20 cm). Plot area for harvest reached 18 m^2 (3 m × 6 m).

The experiment included two factors: nitrogen fertilization (first factor (n = 4): 0, 60, 120, and 180 kg $N \cdot ha^{-1}$) and sulphur fertilization (second factor (n = 3): 0, 20, and 60 kg $S \cdot ha^{-1}$). Nitrogen was applied in the same form and at equal doses, while the sulphur was either applied before sowing (in-soil) or with the top-dressing (foliar) method. The nitrogen fertilization was applied in doses of 60 kg $N \cdot ha^{-1}$ (Table 1). For all the plots with nitrogen, the first dose of the component was sown before sowing as a mixture of borated salpetere (27% N, including: 13.5% $N\text{-}NH_4^+$ and 13.5% $N\text{-}NO_3^-$ and 2% CaO, 4% MgO, and 0.2% B) and ammonium nitrate (34% N, including: 17% $N\text{-}NH_4^+$ and 17% $N\text{-}NO_3^-$). Both fertilizer types, 30 kg $N \cdot ha^{-1}$ was brought in. For the plants fertilized with 120 kg N·ha^{-1}, nitrogen was also applied three to four weeks before rapeseed flowering, and for the plants fertilized with 180 kg N·ha^{-1} it was applied before flowering and at the beginning of flowering. The second and third nitrogen doses were applied only in the form of ammonium nitrate.

Table 1. Pattern of nitrogen and sulphur fertilization in the field experiment

Nutrient	Dose kg·ha^{-1}	Plant development stage				
		pre-sowing	BBCH 13–16	BBCH 35–38	BBCH 50–52	BBCH 61–63
Nitrogen	60	60 borated salpetere + ammonium nitrate (1:1)	–	–	–	–
	120	60 borated salpetere + ammonium nitrate (1:1)	–	–	60 ammonium nitrate	–
	180	60 borated salpetere + ammonium nitrate (1:1)	–	–	60 ammonium nitrate	60 ammonium nitrate
Sulphur	20	sodium sulphate	–	–	–	–
	60	sodium sulphate	–	–	–	–
	20	–	20 sodium sulphate	–	–	–
	60	–	20 sodium sulphate	20 sodium sulphate	–	20 sodium sulphate

When sulphur was applied before sowing (in-soil), both doses (20 and 60 kg S·ha^{-1}) were spread after field smoothing, at the same time. When sulphur was applied using the top-dressing (foliar) method the doses were split. Every fertilized plant received 20 kg S·ha^{-1} once at full emergence, while the plants receiving the dose of 60 kg S·ha^{-1} an additional 20 kg S·ha^{-1} was applied after stem formation and a further 20 kg S·ha^{-1} at the beginning of flowering. Apart from the described diversification in sulphur application methods, all the other agrotechnical elements were identical. Sulphur was applied in the form of anhydrous sodium sulphate (Na_2SO_4 – 22.5% S). Before winter ploughing, phosphorus–potassium–magnesium fertilization was applied in the form of multiple fertilizers, through introducing 100 kg K·ha^{-1}, 26 kg P·ha^{-1}, and 29 kg Mg·ha^{-1}. In every growth season, chemical plant protection was applied according to the recommendations of the Institute of Plant Protection (https://www.ior.poznan.pl).

After harvest, the values of the following parameters were determined for all the plant groups:

- total nitrogen ($N_{og.}$) with the Kjeldahl method using a distiller Kjeltec 2200 by the company Foss,
- total sulphur – with the Inductively Coupled Plasma Optical Emission Spectrometry method after prior sample mineralization in a mixture of concentrated acids: nitrogen(V) and chloric(VII) in a ratio of 4:1.

Seed yield of spring rapeseed, as well as nitrogen and sulphur contents in the seeds have been presented in an earlier paper (Barczak *et al.*, 2016b). On the basis of the data included there, the following parameters were calculated:

- nitrogen and sulphur uptake as a product of the main yield and the contents of elements in it,
- agricultural effectiveness coefficients and nitrogen utilization were calculated according to the following formulas:

$$E_N = (Pl_N - Pl_0)/N \times 100\%$$

where:

E_N – nitrogen effectiveness coefficient, %,
Pl_N – seed yield of spring rapeseed on any plot with application of N and S,
Pl_0 – seed yield of spring rapeseed on the control plot,
N – nitrogen dose,

$$W_N = (P_N - P_0)/N \times 100\%$$

where:

W_N – nitrogen utilization coefficient, %,
P_N – nitrogen uptake with the seed yield of spring rapeseed on any plot with application of N and S,
P_0 – nitrogen uptake with the seed yield of spring rapeseed on the control plot.

Results were subject to analysis of variance for a two-factor experiment, using the program *Statistica* 8.0. Significance of the differences between the average values for the particular fertilization plant groups was evaluated with the Tukey's spread test ($P < 0.05$).

RESULTS AND DISCUSSION

The three-year-long field experiment demonstrated that on average nitrogen and sulphur uptake with spring rapeseed seeds for both sulphur application methods amounted to, respectively, 86.4 kg·ha^{-1} (Table 2) and 26.1 kg·ha^{-1} (Table 3).

Table 2. Nitrogen uptake with spring rapeseed seeds, kg·ha^{-1}

kg N·ha^{-1} A	Year of study												Mean for years			
	I				II				III							
	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean
	0	20	60		0	20	60		0	20	60		0	20	60	
In-soil application of sulphur fertilizer																
0	72.2	100.8	97.9	**90.0**	48.6	71.7	67.1	**62.2**	41.9	58.3	59.1	**52.9**	54.2	77.1	74.9	**68.7**
60	95.6	114.6	134.0	**114.2**	65.2	80.8	94.1	**79.5**	55.1	61.2	69.2	**61.8**	72.2	85.8	99.2	**85.7**
120	107.3	132.3	146.0	**128.3**	70.8	84.4	95.3	**83.3**	59.1	64.5	74.0	**65.6**	79.4	94.2	105.2	**92.9**
180	115.9	139.9	142.7	**132.1**	85.8	100.6	97.9	**94.4**	61.2	72.2	77.7	**70.1**	88.1	104.1	106.4	**99.5**
Mean	**97.5**	**121.8**	**129.9**	**116.3**	**67.3**	**84.1**	**88.7**	**79.9**	**54.1**	**64.1**	**69.9**	**62.7**	**73.5**	**90.3**	**96.4**	**86.7**
LSD$_{0.05}$	A 8.11 B 7.12 A × B 9.03				A 5.25 B 4.21 A × B 6.32				A 3.60 B 4.82 A × B 5.18				A 4.01 B 6.27 A × B 6.96			
Foliar application of sulphur fertilizer																
0	72.2	96.7	82.2	**83.7**	48.6	68.5	56.2	**57.5**	42.7	52.5	45.9	**47.1**	54.2	72.4	61.5	**62.7**
60	95.6	115.7	133.6	**114.6**	65.2	89.0	86.7	**80.2**	55.1	71.2	62.2	**62.8**	72.2	92.1	94.4	**86.2**
120	107.3	124.2	149.4	**126.4**	70.8	104.3	90.6	**88.1**	59.1	78.6	70.3	**69.3**	79.4	102.5	104.1	**95.3**
180	115.9	139.8	147.5	**134.3**	85.8	101.4	99.7	**95.6**	61.2	76.1	73.1	**69.9**	88.1	105.8	107.1	**100.3**
Mean	**97.5**	**118.7**	**126.7**	**113.9**	**67.3**	**90.6**	**82.9**	**79.8**	**54.3**	**69.4**	**62.8**	**62.0**	**73.5**	**93.2**	**91.8**	**86.1**
LSD$_{0.05}$	A 7.92 B 6.91 A × B 8.18				A 5.51 B 4.93 A × B 6.27				A 3.94 B 4.46 A × B 5.34				A 2.89 B-3.92 A × B 4.56			

A – nitrogen fertilization; B – sulphur fertilization

Table 3. Sulphur uptake with spring rapeseed seeds, kg·ha^{-1}

kg N·ha^{-1} A	Year of study												Mean for years			
	I				II				III							
	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean
	0	20	60		0	20	60		0	20	60		0	20	60	
In-soil application of sulphur fertilizer																
0	21.8	31.2	30.9	**28.0**	14.6	24.2	22.5	**20.4**	12.7	19.2	19.6	**17.0**	16.4	25.1	24.5	**22.0**
60	28.4	37.0	40.7	**35.4**	19.4	24.6	28.3	**24.1**	16.2	18.8	21.8	**18.9**	21.3	26.6	30.4	**26.1**
120	31.4	40.7	44.4	**38.8**	21.2	25.6	28.2	**25.0**	17.0	19.2	23.0	**19.6**	23.2	28.4	32.0	**27.9**
180	33.0	38.9	43.0	**38.0**	23.6	27.7	28.7	**26.7**	17.3	19.5	22.9	**19.8**	24.6	28.5	31.5	**28.2**
Mean	**28.7**	**37.0**	**39.8**	**35.0**	**19.7**	**25.5**	**26.9**	**24.0**	**15.8**	**19.2**	**21.8**	**18.9**	**21.4**	**27.2**	**29.6**	**26.1**
LSD$_{0.05}$	A 2.51 B 2.20 A × B ns				A 1.75 B 1.53 A × B 2.42				A 2.10 B 1.89 A × B 2.32				A 1.77 B 1.21 A × B 1.41			
Foliar application of sulphur fertilizer																
0	21.8	31.6	28.0	**26.9**	14.6	23.0	20.2	**19.1**	12.7	17.7	16.6	**15.7**	16.4	24.1	21.8	**20.8**
60	28.4	37.1	41.2	**35.3**	19.4	27.5	27.0	**24.7**	16.2	21.9	19.6	**19.3**	21.3	28.8	29.4	**26.5**
120	31.4	37.8	45.5	**37.9**	21.2	30.8	26.2	**25.9**	17.0	22.8	21.8	**20.6**	23.2	30.5	31.2	**28.3**
180	33.0	40.7	42.8	**38.6**	23.6	29.3	28.2	**27.0**	17.3	21.2	21.5	**19.9**	24.6	30.4	31.0	**28.6**
Mean	**28.8**	**36.8**	**39.4**	**34.8**	**19.8**	**27.7**	**25.6**	**24.4**	**15.7**	**20.9**	**19.9**	**18.8**	**21.4**	**28.5**	**28.4**	**26.1**
LSD$_{0.05}$	A 2.92 B 2.68 A × B 3.13				A 1.95 B 1.84 A × B ns				A 1.54 B 1.42 A × B 2.07				A 1.60 B 1.43 A × B 1.78			

A – nitrogen fertilization; B – sulphur fertilization
ns – non-significant differences

The plants took up the highest amount of the discussed elements with seed yield (on average 115.1 kg N·ha^{-1} and 34.9 kg S·ha^{-1}) in the first year of the study, in which favourable weather conditions (Barczak *et al.*, 2016a) were conducive to high yield (Barczak *et al.*, 2016b) and high macroelement accumulation. The lowest amount of the elements was taken up in the third year of the study (62.4 kg N·ha^{-1} and 18.9 kg S·ha^{-1}). Nitrogen fertilization, as the strongest yield-forming factor in plant production, in all the study years significantly affected the accumulation of this element in the rapeseed main yield. The difference in the element accumulation between the seeds of plants fertilized exclusively with nitrogen (no sulphur) and the ones that originated from the control group (no nitrogen or sulphur), for 60, 120, and 180 kg N·ha^{-1} amounted to, on average: 32.0%, 45.2%, and 61.1%. In the case of exclusive sulphur fertilization (no nitrogen), a clearly higher nitrogen uptake occurred with the in-soil application (on average 68.7 kg N·ha^{-1}) than with foliar application (on average 62.7 kg N·ha^{-1}). For both sulphur application methods (no nitrogen fertilization), in all the growth seasons, with the exception of in-soil application in the third year of the study, a significantly higher nitrogen uptake was ensured by 20 kg S·ha^{-1} rather than by 60 kg S·ha^{-1}. This fact is the result of the lower yield-forming effectiveness of the dose of 60 kg S·ha^{-1} than of 20 kg S·ha^{-1} in the conditions of a lack of simultaneous nitrogen application (Barczak *et al.*, 2016b).

Supplementation of nitrogen fertilization with sulphur caused, in comparison with the control plants, a significant increase in nitrogen accumulation in rapeseed seeds for every combination of the studied fertilization components. For each method of sulphur application, the highest uptake of this element with seed yield was obtained with the simultaneous application of the highest doses of the studied elements: 180 kg N·ha^{-1} and 60 kg S·ha^{-1}.

The effect of sulphur on nitrogen uptake with rapeseed seed yield that has been confirmed in the present study is the result of the structural and metabolic functions of this element, as it constitutes a component of, among others, amino acids, and therefore of proteins and protein enzymes. Sulphur takes part in the synthesis of proteins, carbohydrates, fats, and vitamins, which justifies its yield-forming effect. Therefore, already at the molecular level, there is a strong functional relation between sulphur and nitrogen. Yield increase as a result of feeding on sulphur is related mostly to balancing the nitrogen taken up by plants (Grzebisz, 2008). Sulphur increases the effectiveness of fertilizer and soil nitrogen, as well as increasing plant tolerance to biotic stress (diseases) and abiotic stress (unfavourable hydrothermal conditions), which also contributes to yield increase (Klikocka and Sachajko, 2011; Wielebski, 2015). Moreover, plants well fed with sulphur contain more chlorophyll, which causes an increase in photosynthesis intensity, the result of which is an increase in plant mass. This fact was confirmed in the study by Lencioni *et al.* (1997), who demonstrated a 25% decrease in chlorophyll a and b content and a decrease in photosynthetic activity of rapeseed plants in the conditions of sulphur shortage. Optimum supply of this element in rapeseed plants is conducive to protein synthesis and high yield. The result of the positive sulphur effect on nitrogen content and yield is an increase in nitrogen uptake in seeds.

In all the study years, sulphur accumulation in the seed yield of rapeseed fertilized exclusively with nitrogen (no sulphur) was significantly higher than in the seeds of rapeseed from the control plot (Table 3). For nitrogen doses 60, 120, and 180 kg·ha^{-1}, differences amounted to, respectively, 29.1%, 40.6%, and 49.1%. In the conditions of exclusive sulphur application (no nitrogen), its slightly higher uptake was found after in-soil application of this element (on average 22.0 kg·ha^{-1}) than after foliar application (on average 20.8 kg S·ha^{-1}), which may be the result of the higher effectiveness of sulphur fertilizers applied in-soil before sowing. Krauze and Bowszys (2001) point to a higher effectiveness of this component applied directly into the soil in comparison with foliar application in spring rapeseed cultivation, as did Barczak (2010) in white mustard cultivation. Foliar fertilization has many advantages: it is characterized by a high speed of nutrient action, the possibility of avoiding nutrient biological and chemical sorption in the soil, as well as the possibility of applying fertilizers with plant protection means. However, a serious disadvantage of this application method of fertilizers is a dependency on the weather conditions, as well as the risk of leaf burning, especially when the solutions are of too high concentration or when the treatment is carried out in improper thermal conditions.

Exclusive sulphur fertilization significantly increased the uptake of sulphur in rapeseed seeds in relation to unfertilized rapeseed. Application of 20 kg S·ha^{-1} caused, on average, an uptake increase of 52.1% (in-soil application) and of 46.1% (foliar application), while the application of 60 kg S·ha^{-1} caused an increase, respectively, by 48.5% and 32.1%. In all the study years, regardless of the sulphur application method (with the exception of in-soil sulphur application in the third year of the study), a lower uptake of this element was found in plants that had the dose of 60 kg S·ha^{-1} in comparison with the dose of 20 kg S·ha^{-1}, which is the result of the lower effectiveness of a higher sulphur dose applied without nitrogen.

Joint application of nitrogen and sulphur usually significantly increased sulphur uptake with seeds, both in relation to the seed yield of the control plants and from the plots fertilized exclusively with nitrogen or sulphur. The highest sulphur uptake for both methods of its application was found with the simultaneous application of 120 kg N·ha^{-1} and 60 kg S·ha^{-1}

In order to perform the evaluation of production effectiveness of fertilization in the conducted experiment, the agricultural effectiveness of nitrogen was calculated, which expressed the increase in the seed yield of spring rapeseed in kg per 1 kg of the applied component (Table 4). The above indicator is a measure of a plants ability to process nitrogen taken up by it in the commercial yield (Kruczek and Szulc, 2000). The agricultural effectiveness of nitrogen, depending on the study year, amounted to, on average, 5.34 to 12.61 kg of seeds per 1 kg of nitrogen in the experiment with in-soil sulphur application and 5.55 to 12.26 kg of seeds in the conditions of foliar sulphur application (Table 4).

A high diversification of the values of the discussed parameter were found depending on the study year. In the first year, with the most favourable hydrothermal conditions (Barczak *et al.*, 2016a), the nitrogen agricultural effectiveness amounted to, on average for both application methods, 12.4 kg of seeds per 1 kg of nitrogen, and in the third year, in which from May to July a precipitation shortage occurred (total precipitation was only 136.0 mm, which is 65% of the many-years' average for those months) and temperature was visibly higher than average, the discussed indicator had the value, on average, of about 5.4 kg of seeds per 1 kg of nitrogen. Spring rapeseed responded with seed yield increase under the effect of nitrogen fertilization (Barczak *et al.*, 2016b), but the yield-forming effect of this component with an increase in fertilization varied to different degrees in different years.

As nitrogen doses increased, applied with no sulphur, the indicator decreased on average for the three study years to 8.66 for 60 kg N·ha^{-1} and to 4.95 for 180 kg N·ha^{-1} (difference of 42.8%). The above tendency persisted also on the plots on which, in addition to nitrogen, sulphur was applied, but the decrease in the discussed factor as nitrogen doses increased was higher and amounted to, depending on the variant, 57.1% to 60.6%.

Table 4. Agricultural effectiveness of fertilizer nitrogen in spring rapeseed cultivation, kg·ha^{-1}

kg N·ha^{-1} A	Year of study												Mean for years			
	I				II				III							
	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean
	0	20	60		0	20	60		0	20	60		0	20	60	
In-soil application of sulphur fertilizer																
60	11.50	18.67	23.3	**17.82**	8.16	14.3	17.67	**13.38**	6.33	7.67	9.50	**7.83**	8.66	13.55	16.82	**13.01**
120	8.58	13.42	14.4	**12.10**	5.42	7.75	9.00	**7.39**	4.00	4.58	5.75	**4.78**	6.00	8.58	9.72	**8.10**
180	6.67	7.94	9.1	**7.90**	5.56	6.28	6.39	**6.08**	2.61	3.22	4.38	**3.40**	4.95	5.81	6.62	**5.79**
Mean	**8.92**	**13.34**	**15.6**	**12.61**	**6.38**	**9.44**	**11.02**	**8.95**	**4.31**	**5.16**	**6.54**	**5.34**	**6.53**	**9.31**	**11.05**	**8.97**
LSD$_{0.05}$	A 2.23 B 1.91 A × B 2.36				A 1.75 B 1.56 A × B ns				A 0.92 B 1.04 A × B 1.14				A 1.24 B 0.92 A × B 1.01			
Foliar application of sulphur fertilizer																
60	11.50	17.83	23.50	**17.61**	8.16	17.30	14.33	**13.26**	6.33	11.67	6.33	**8.11**	8.66	15.60	14.72	**12.99**
120	8.58	10.00	14.91	**11.16**	5.42	11.41	7.66	**8.16**	4.00	7.16	4.58	**5.25**	6.00	9.52	9.05	**8.19**
180	6.67	8.50	8.83	**8.00**	5.56	6.83	6.11	**6.17**	2.61	4.05	3.22	**3.29**	4.95	6.46	6.05	**5.82**
Mean	**8.92**	**12.11**	**15.75**	**12.26**	**6.38**	**11.85**	**9.37**	**9.20**	**4.31**	**7.63**	**4.71**	**5.55**	**6.53**	**10.53**	**9.94**	**9.00**
LSD$_{0.05}$	A 2.27 B 1.85 A × B 2.44				A 1.65 B 1.19 A × B 1.52				A 1.02 B ns A × B 0.91				A 0.92 B 1.74 A × B 1.35			

A – nitrogen fertilization; B – sulphur fertilization
ns – non-significant differences

In all of the study years, sulphur supplementation at the dose of 20 kg·ha^{-1}, regardless of its application method, caused a significant increase in the agricultural effectiveness of every nitrogen dose. In-soil application of 60 kg S·ha^{-1} in every study year significantly increased nitrogen effectiveness in comparison with the dose of 20 kg S·ha^{-1}. On the plot with foliar sulphur application, this occurrence was noted only in the first year of the study, which was characterized by the most favourable weather conditions (Barczak *et al.*, 2016a). After in-soil sulphur application, the highest nitrogen effectiveness was obtained for fertilization with 60 kg N·ha^{-1} and 60 kg S·ha^{-1} (16.82 kg of seeds per 1 kg of nitrogen), and after foliar application the highest nitrogen effectiveness was for the combination of 60 kg N·ha^{-1} and 20 kg S·ha^{-1} (15.60 kg of seeds per 1 kg of nitrogen). Research by many authors indicates that increased nitrogen effectiveness may be obtained through a proper supply of sulphur to plants (Jamal *et al.*, 2005; Wielebski, 2011; Podleśna, 2013). In the conditions of intensive nitrogen fertilization and sulphur shortage, yield reduction and a decrease in its quality occurs (Krauze and Bowszys, 2001). According to Bloem (1998), a sulphur shortage clearly decreases the effectiveness of nitrogen applied in fertilizers, which may lead to a yield decrease by even up to 50%.

According to numerous authors (Kruczek and Szulc, 2000; Małecka and Blecharczyk, 2005), a good measure of the effectiveness of nitrogen fertilization is the coefficient of nitrogen utilization from fertilizers, which is defined as the amount of nitrogen taken up with the yield per unit of the component applied in fertilizers. At present, environmental protection concerns are requiring research into the effects of chemical production means that are used in agriculture, including mineral fertilizers (Trawczyński and Wierzbicka, 2014). Among fertilizer components, nitrogen requires particular attention, since it is a biogenic element. It is characterized by high lability, as it easily escapes into the atmosphere and contributes to the occurrence of acid rain. It may also undergo rinsing into the soil profile and move into groundwater (Grzebisz, 2008).

In the present study, the highest nitrogen utilization from fertilizers took place in the first study year (Table 5), in which the weather conditions were the most conducive to high rapeseed productivity (Barczak *et al.*, 2016a), thanks to which yield size, as well as the element uptake, were high, and the utilization reached, on average, 50.4%. Significantly lower values of this coefficient were obtained in the subsequent study years (in the second year on average 36.6%, in the third year 23.2%). A somewhat higher nitrogen utilization was found with foliar sulphur application (on average 37.2%) than was found with the in-soil application (36.3%), especially in the dry years (second and third years of the study). Under conditions not conducive to mineralization and soil nitrogen uptake, the effectiveness of foliar sulphur application may be higher than that of in-soil application (Barczak, 2010). Sulphur is a component relatively easily taken up by plant leaves (Podleśna, 2009). This element is absorbed faster by the above-ground plant parts than are calcium, phosphorus, and microelements. It is estimated that through foliar application, sulphur is taken up, depending on the conditions, from several to several dozen times faster in comparison with in-soil application (Grześkowiak, http://www.agrotechnika.suwalki.pl/zasady.htm).

The utilization of fertilizer nitrogen applied with no sulphur amounted to, on average, 22.7%. It decreased with an increase in dose from a level of 29.1% for 60 kg N·ha^{-1} to 18.4% for 180 kg N·ha^{-1} (Table 5). Sulphur supplementation, like in the studies by Fotyma *et al.* (2003), with winter rapeseed, maize for grain, and spring and winter wheat, increased nitrogen utilization under both application methods, while limiting the possibility of its loses. In all the study years, on the plots fertilized with nitrogen and sulphur at the dose of 20 kg·ha^{-1} (regardless of the application method), the value of the discussed indicator was significantly higher in relation to the plants fertilized only with nitrogen. In-soil application of 60 kg S·ha^{-1} in combination with the doses of 60 and 120 kg N·ha^{-1} caused a statistically confirmed further increase in nitrogen utilization in all the study years. However, for foliar fertilization, the above occurrence was observed only in the first study year. In all years with the in-soil sulphur application, the highest nitrogen utilization occurred after the application of 60 kg N·ha^{-1} and 60 kg S·ha^{-1}, and with the foliar sulphur application, the above combination was the most favourable only in the first year of the study.

The discussed changes regarding the uptake, effectiveness and utilization of nitrogen by spring rapeseed, obtained as a result of sulphur supplementation, indicate that the presence of sulphur increases the effectiveness of nitrogen fertilization, which may have not only positive economic, but also environmental effects, since it limits the possibility of nitrogen dispersion and loss.

Table 5. Utilization of fertilizer nitrogen in spring rapeseed cultivation, %

kg N·ha^{-1} A	Years of study												Mean for years			
	I				II				III							
	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean	kg S·ha^{-1} – B			mean
	0	20	60		0	20	60		0	20	60		0	20	60	
	In-soil application of sulphur fertilizer															
60	39.0	70.7	102.9	**70.1**	27.6	53.6	75.8	**52.3**	20.7	32.1	45.5	**32.8**	29.1	52.1	74.7	**51.9**
120	29.2	50.1	61.5	**46.8**	18.5	29.8	38.9	**29.1**	13.7	18.8	26.8	**19.8**	20.5	32.9	42.4	**31.9**
180	24.3	37.6	39.2	**33.3**	20.6	28.8	27.3	**25.6**	10.3	16.8	19.9	**15.6**	18.4	27.7	28.8	**25.0**
Mean	**30.8**	**52.8**	**67.9**	**50.3**	**22.3**	**37.4**	**47.3**	**35.7**	**14.9**	**22.6**	**30.7**	**22.7**	**22.7**	**37.6**	**48.6**	**36.3**
LSD$_{0.05}$	A 4.52 B 4.40 A × B 5.29				A 3.21 B 2.86 A × B 3.33				A 2.14 B 1.25 A × B 2.08				A 1.84 B 1.22 A × B 1.94			
	Foliar application of sulphur fertilizer															
60	39.0	72.5	102.3	**71.3**	27.6	67.3	63.5	**52.8**	20.7	47.5	32.5	**33.6**	29.1	62.4	66.1	**52.5**
120	29.2	43.3	64.3	**45.6**	18.5	46.4	35.0	**33.3**	13.7	29.9	23.0	**22.2**	20.5	39.9	40.8	**33.7**
180	24.3	37.6	41.8	**34.6**	20.7	29.3	28.4	**26.1**	10.3	18.6	16.9	**15.3**	18.4	28.5	29.0	**25.3**
Mean	**30.8**	**51.1**	**69.5**	**50.5**	**22.3**	**47.7**	**42.3**	**37.4**	**14.9**	**32.0**	**24.1**	**23.7**	**22.7**	**43.6**	**45.3**	**37.2**
LSD$_{0.05}$	A 3.65 B 4.81 A × B 3.94				A 3.47 B 2.84 A × B 3.68				A 2.46 B 2.17 A × B 2.85				A 1.95 B 1.59 A × B 2.14			

A – nitrogen fertilization; B – sulphur fertilization

CONCLUSIONS

1. The results from the conducted research show that the weather conditions in particular growth seasons had a significant effect on nitrogen and sulphur uptake in the seed yield of spring rapeseed, and also on the agricultural effectiveness and nitrogen utilization from fertilizers.
2. Nitrogen uptake with the seed yield of spring rapeseed, as well as nitrogen agricultural effectiveness and utilization from fertilizers was higher under the conditions of joint fertilization with nitrogen and sulphur than it was with no sulphur application.
3. The joint application of different nitrogen doses and 60 kg S·ha^{-1} usually made it possible to obtain the highest values of the studied parameters in every growth season.
4. The sulphur application method only clearly diversified the uptake of the studied elements in the seed yield of spring rapeseed when it was fertilized only with sulphur. The agricultural effectiveness and nitrogen utilization in relation to this factor were only diversified to a low extent.

5. The obtained results indicate that sulphur supplementation through its effect on nitrogen uptake and its agricultural effectiveness and utilization from fertilizers may have positive economic and environmental consequences.

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SIARKA JAKO CZYNNIK KSZTAŁTUJĄCY EFEKTYWNOŚĆ AZOTU W AGROTECHNICE RZEPAKU JAREGO. CZ. III. EFEKTYWNOŚĆ ROLNICZA I WYKORZYSTANIE AZOTU

Streszczenie

Podstawę badań stanowiło trzyletnie ścisłe doświadczenie polowe, realizowane na czarnej ziemi zdegradowanej, o odczynie obojętnym i niskiej zasobności w przyswajalną siarkę. Dwuczynnikowe doświadczenie założono w układzie równoważnych bloków. Czynnikiem I rzędu były dawki azotu (w kg·ha^{-1}: 0, 60, 120, 180), czynnikiem II rzędu – dawki siarki (w kg·ha^{-1}: 0, 20, 60). Dodatkowym aspektem badań było zróżnicowanie sposobów stosowania siarki (przedsiewnie – doglebowo oraz pogłównie – dolistnie). Uprawiano rzepak jary odmiany populacyjnej Star. Z przeprowadzonych badań wynika, ze warunki pogodowe w poszczególnych sezonach wegetacyjnych miały znaczący wpływ na pobranie azotu i siarki z plonem nasion rzepaku jarego, a także na efektywność rolniczą i wykorzystanie azotu z nawozów. W każdym sezonie wegetacyjnym wartości badanych parametrów były większe w warunkach łącznego nawożenia azotem i siarką niż bez siarki. Sposób aplikacji siarki wyraźnie różnicował tylko pobranie badanych pierwiastków z plonem nasion rzepaku jarego nawożonego wyłącznie tym składnikiem. Uzyskane wyniki wskazują, że suplementacja siarki poprzez wpływ na pobranie azotu oraz jego efektywność rolniczą i wykorzystanie z nawozów może mieć pozytywne skutki ekonomiczne i ekologiczne.

Słowa kluczowe: *Brassica napus* L., nawożenie, pobranie azotu, pobranie siarki, rośliny oleiste