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The effect of fertilization with sulphur on uptake and utilization of nitrogen by winter wheat

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Abstract. This paper presents the results of a four-year field study on the effect of sulphur fertilization on nitrogen uptake and its utilization efficiency by winter wheat. A two-factor field experiment was carried out over 1999–2002 in a randomized blocks design. The first factor was fertilization with sulphur (in the form of sulphate) in doses of 0 and 60 kg ha^{-1}, while the second factor – nitrogen fertilization (in the form of ammonium nitrate) in doses of 0, 30, 60, 90, 120 and 150 kg N ha^{-1}. Nitrogen was applied in doses of 30 kg N ha^{-1}, at two-week intervals after the start of growing season. The research showed that sulphur fertilization increased on average the nitrogen uptake by wheat by 3.5%. The efficiency index of nitrogen fertilization of wheat had higher values after application of fertilizers containing sulphur with a tendency to decrease as the dose N increased. Sulphur fertilization increased the agronomic efficiency of nitrogen in the range of low doses from 30 to 90 kg N ha^{-1}.

Keywords: nitrogen doses, sulphur fertilization, nitrogen uptake, efficiency of nitrogen utilization

INTRODUCTION

Most Polish mineral soils are characterized by a low content of total sulphur, which in the arable layer of cultivated soils, ranges between 0.01–0.15%. The average content of sulphur in Polish soils is assumed to be between 15 and 20 mg S $(100\ g)^{-1}$ of soil (Motowicka-Terelak, Terelak 1998). According to Król (1978), sulphur occurs in about 30% in mineral form and about 70% in organic form. According to Lityński and Jurkowska (1982), the proportion of organic sulphur in the humus horizons of mineral soils is 50–80%, while in organic soils it reaches 97%. In agriculturally used soils, only 10% of total sulphur is in forms easily available to plants, 90% of which comes from organic sulphur (Diamont, Hanley, 1970). The release of mineral sulphur into the soil from organic compounds occurs when the C:S ratio in the microbial decomposed substance is less than 200. Under aerobic conditions, the product of mineralisation of organic sulphur compounds is sulphate (Motowicka-Terelak, Terelak, 1998).

Plants take up sulphur in the form of anions (SO_4^{-2}) in the range pH 4–7. Other naturally occurring forms of sulphur, such as thiosulphates, polithionates, and elemental sulphur, must first be oxidized to sulphates or reduced to sulphides before they can enter the sulphur amino acid biosynthesis reaction (Król, 1978; Sulphur Institute Materials, 1995). Cereal crops and grasses (e.g. wheat) have the lowest sulphur requirement. This requirement ranges from 12–25 kg S ha^{-1} rok^{-1} (Podleśna, 2013). It was found that wheat needs about 3 kg S ha^{-1} to produce 1 ton of seeds with an equivalent amount of straw (Zhao et al., 1999).

Sulphur metabolism in the plant is closely related to nitrogen metabolism (De Kok et al., 2002) and deficiency of one component inhibits the action of the other (Janzen et al., 1984). The degree of sulphur uptake and utilization by plants is dependent on soil nitrogen availability. The optimum N:S ratio, depending on the plant species, should be 15–10:1 (Blake-Kalff et al., 2002). The optimum ratio of nitrogen to sulphur in whole winter wheat plants before flowering is 1:0.68, according to Grzebisz (1997). The issue of N:S ratio also has an environmental dimension, as sulphur deficiency leads to lower efficiency and nitrogen utilization rates of commonly used nitrogen fertilizers (Brown et al., 2000).

The yield-forming role of nitrogen in relation to cereals is supported by the results of numerous experiments (Boreczek, 2000; Fotyma, 1997, 1999). On the other hand, the total nitrogen uptake is always higher for plants fertilized with sulphur, which is significantly influenced by the pool of the component accumulated in seeds (Podleśna, 2013).

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The objective of this study was to determine the effect of sulphur fertilization on nitrogen uptake and utilization by winter wheat.

MATERIALS AND METHODS

In 1999–2002, studies on winter wheat of Kobra cultivar were carried out in a long-term, static field experiment located at the Agricultural Experimental Station Grabów n. Wisła (Mazowieckie voivodeship), in a randomized sub-block design in four replications, far from industrial centers, where no manure had been used for many years and the soil had a natural, low sulphur content (0.12–0.18 mg S-SO_4 (100 g)$^{-1}$ of soil) (Terelak, Motowicka-Terelak, 1998). In a two-factorial experiment carried out on lessive soil formed from light clay containing from 26 to 35% of silt and clay fraction, belonging to very good rye complex, winter rapeseed, winter wheat, maize and spring wheat were grown in a four-field crop rotation. The first experimental factor was sulphur fertilization and the second was nitrogen fertilization. In the treatment without sulphur, NPK fertilizers (nitrogen – ammonium nitrate 34%, phosphorus – granular potassium superphosphate 46%, potassium – granular potassium salt 60%) not containing this component were applied, while in the treatment with sulphur – NPKS fertilizers mentioned above plus sulphur in the form of potassium sulphate 50%, simple superphosphate 32% were used. PKS fertilizers were applied before sowing. The doses of NPKS were adjusted to the nutrient requirements of the crop. The average dose of sulphur introduced with these fertilizers was about 20 kg S ha^{-1} (1999 – 21, 2000 – 22, 2001 – 20, 2002 – 20 kg S·ha^{-1}). Nitrogen fertilizers, in the form of ammonium nitrate, were applied in 6 doses: 0, 30, 60, 90, 120 i 150 kg N ha^{-1}. Nitrogen was applied in doses of 30 kg N ha^{-1}, at two-week intervals after the start of growing season. The area of plots to be harvested was 19.75 m^2. The plants were harvested at full maturity stage. After harvest, grain (at 15% humidity) and straw yields were determined and nitrogen content (Kjeldahl metod) of green tops was determined, and then its uptake was calculated. Next, the efficiency indices of nitrogen fertilization under sulphur fertilization and without sulphur were calculated in the form of nitrogen utilization from fertilizers (W_N), agricultural efficiency of fertilization (A_{NE}) and physiological efficiency of nitrogen (P_{NE}).

The indicators in question were calculated using the following formulas (Pecio, 2017):

Nitrogen use efficiency from fertilizers (W_N) by plants:

$$W_N = [(Un - Uk)/D] \cdot 100\%$$

where:
Un – total uptake of nitrogen in the treatment with N fertilization, kg ha^{-1},
Uk – total uptake of nitrogen in the treatment without N fertilization, kg ha^{-1},
D – nitrogen input in the fertiliser, kg ha^{-1}.

Agricultural efficiency of nitrogen – A_{NE}

$$A_{NE} = (YN - Y0)/N$$

Physiological efficiency of nitrogen – P_{NE}

$$P_{NE} = (YN - Y0)/(PN - P0)$$

where:
YN – grain yield in the treatment with N fertilization,
Y0 – grain yield in the control treatment without N fertilization,
N – nitrogen input in the YN treatment,
PN – nitrogen uptake with crop yield at the YN treatment,
P0 – nitrogen uptake with crop yield in control treatment Y0.

The results of the study were processed by analysis of variance (ANOVA) using Statistica 10.1 statistical software. The significance of differences was determined using Tukey's test at the significance level = 0.05.

WEATHER CONDITIONS

The 1998/1999 growing season saw the highest precipitation of 641 mm. After sowing, which took place in the 3rd decade of September, heavy rains fell which, on the one hand, caused the crusting of the topsoil and, on the other hand, improved water conditions in the soil. The vegetation started at the beginning of March, whereas in April and June the monthly rainfall significantly exceeded the multi-year norm. In spite of humid weather conditions that promoted the development of fungal diseases, a satisfactory grain yield was obtained at the level of 6 t ha^{-1}.

The second period of the study (1999–2000) saw less rainfall (622 mm). After sowing the seeds (in October), abundant rains occurred, which significantly improved the soil water balance. After overwintering, from the second decade of April, high daily temperatures, which caused significant transpiration of water from the soil. The negative water balance in the period from shooting to flowering resulted in soil drought which became severe at the end of June and accelerated plant ripening.

The third period of the study (2000–2001, with rainfall 619 mm) started with intense rainfall in the second decade of September. This was followed by a drought phase lasting until the end of October, which in effect inhibited plant development. During winter, high temperatures accompanied by lack of snow cover occurred. Thus, there were fears of hardening off and freezing of plants, especially in the early spring, but eventually the plants survived this period in quite good condition. The spring and summer of 2001 brought varied temperature and moisture conditions. A very wet April was followed by dry first two decades of May, followed by further rainfall from the 3rd decade of May. The amount and distribution of the rainfall improved considerably and had a beneficial effect on the condition of plants which resulted in the grain yield at the level of 5.8 t ha^{-1}.

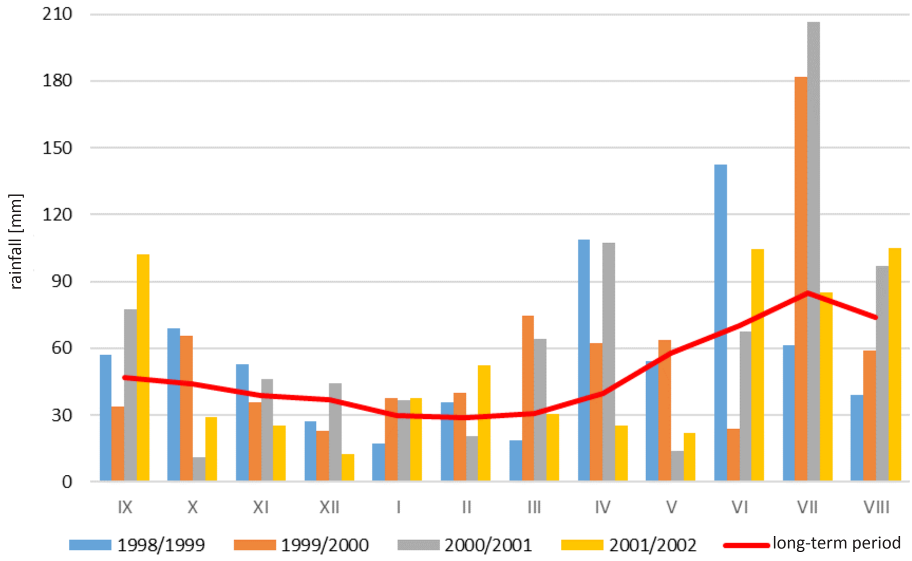

Figure 1. Rainfall during the 1998–2002 growing seasons compared to the long-term period.

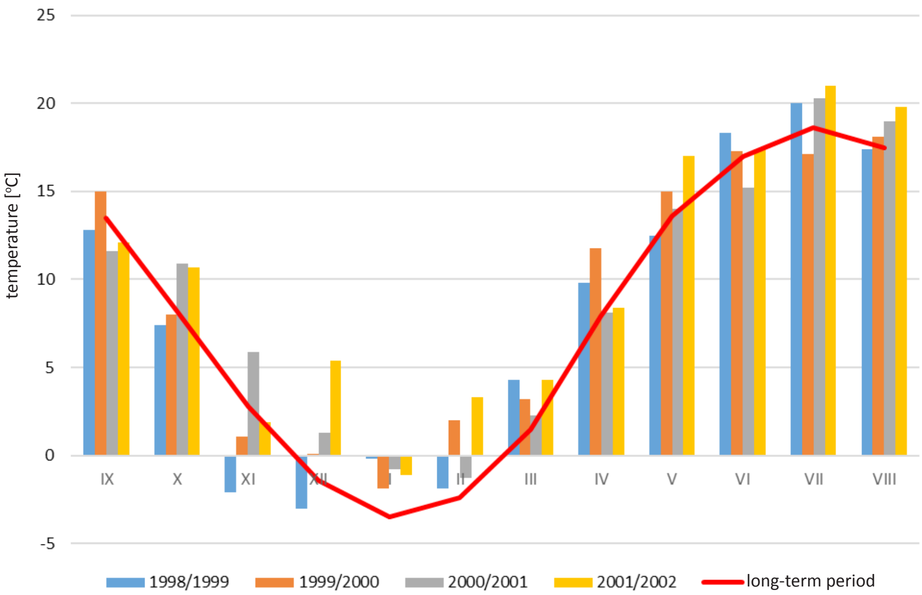

Figure 2. Air temperature during the 1998–2002 growing seasons compared to the long-term period.

Table 1. ANOVA results for the main effects.

Effect	One-dimensional significance tests for N uptake				
	SS	Df	MS	F	P
Free term	3176220	1	3176220	18238.79	0.00
Sulfur	586	1	586	3.36	0.07
N dose	340647	5	68129	391.22	0.00
Sulfur × N dose	118	5	24	0.14	0.98
Error	31346	180	174		

SS – sum of squares, Df – degrees of freedom, MS – mean square, F – mean squares quotient, p – level of significance

In the last period of the study (2001–2002) with total precipitation (425 mm), grain sowing occurred in well-humidified soil. In winter, from the third decade of January, air temperatures increased considerably as a result of which the snow cover disappeared and plants were stimulated to further vegetation. Also in February, the average monthly temperature was positive and amounted to 3.3°C (with the long-term mean of -2.4°C). The warm winter affected the development of plants, which at the beginning of April had developed 5–6 lateral shoots. Since April weather conditions have changed. Weak precipitation in April and its lack in the first half of May (drought as in the second year of the study), and high temperatures caused inhibition and differentiation of further growth and development of plants. The weather conditions affected the obtained grain yield which on average amounted to 5.1 t ha^{-1}.

In summary, the years 2000 and 2002 had very similar weather patterns of prolonged drought during the grain formation period.

The distribution of precipitation and total temperatures from 1999 to 2002 are shown in Figures 1 and 2.

RESULTS

Nitrogen uptake

Nitrogen uptake by winter wheat increased up to the highest nitrogen dose applied in the experiment of 150 kg N ha^{-1}, which for the maximum yield, both with and without sulphur fertilization, was 191.4 kg N ha^{-1}. Sulphur fertilization resulted in a non-significant increase in nitrogen uptake against increasing N rates (Table 1). On average, the treatments fertilized with sulphur took up by 3.5 kg N ha^{-1} more compared to treatments not fertilized with this component (Table 2, Fig. 3).

Table 2. Nitrogen uptake by winter wheat [kg ha^{-1}] – average from 1999–2002.

N dose [kg ha^{-1}]	Total nitrogen uptake		
	- S	+ S	mean for N dose
0	66.0	68.6	67.3
30	88.0	92.6	90.3
60	116.0	120.6	118.3
90	138.6	143.2	140.9
120	161.4	165.6	163.5
150	191.2	191.6	191.4
Mean	126.9	130.4	128.6
$LSD_{0.05}$	non significant		

Nitrogen efficiency indicators

The average efficiency of fertilizer nitrogen (W_N) utilization by winter wheat was high and ranged from 79.7 to 85.0% for the object with the lowest and highest N dose, respectively (Table 3). Under sulphur fertilization, nitrogen use efficiency was on average 7.4 pp. higher compared to the treatments without sulphur. Mineral sulphur caused an increase in nitrogen use from fertilizers at each N dose, but the highest value of this index was found in treatments fertilized with lower N doses, i.e. 30–60 kg N ha^{-1}.

Of the application rates used in the experiment, the highest agricultural efficiency (A_{NE}) was achieved for N 30 kg N ha^{-1} +S (36.7 kg). The beneficial effect of sulphur fertilization on increasing agricultural efficiency was observed in the range of low N 30–90 kg N ha^{-1} (Table 3).

The highest physiological efficiency was found for the dose of N 30 kg N ha^{-1} (42.3 and 41.4 kg), while the lowest for the dose N 150 kg N ha^{-1} adequate for -S and +S (24.5 and 22.1 kg) (Table 2). The effect of sulphur fertilization

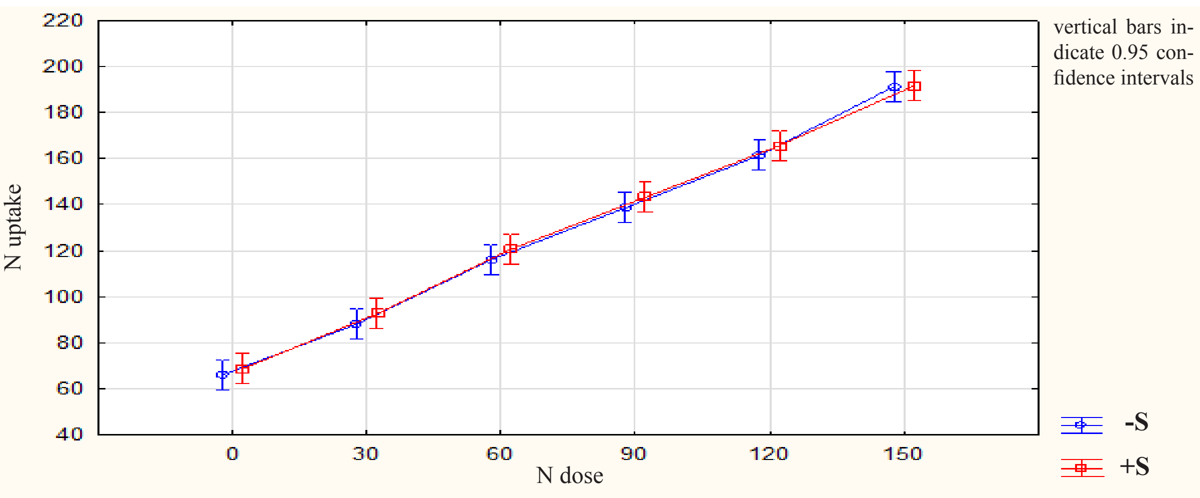

Figure 3. Nitrogen uptake in dependency on fertilization with this nutrient [kg ha^{-1}].

Table 3. Indexes of efficiency of nitrogen use.

N dose (kg ha^{-1})	W_N Apparent nitrogen recovery [%]			A_{NE} Agronomic efficiency of nitrogen [kg of grain kg^{-1} N]		P_{NE} Physiological efficiency of nitrogen [kg of grain kg^{-1} N]	
	- S	+ S	Average for N dose	- S	+ S	- S	+ S
30	70.8	88.6	79.7	31.0	36.7	42.3	41.4
60	83.4	91.1	87.2	28.3	31.3	34.0	34.4
90	80.6	85.8	83.2	25.1	27.1	31.1	31.6
120	79.5	83.0	81.3	23.1	22.1	29.0	26.6
150	83.5	86.4	85.0	20.5	18.5	24.5	22.1
Average	79.6	87.0	83.3	25.6	27.1	32.2	31.2

on the physiological efficiency of nitrogen proved to be ambiguous (Table 3). In most of the N+S-fertilized treatments, the values of this index were lower compared to the +N plots, i.e. not fertilized with sulphur fertilizer.

DISCUSSION

It was shown that on a control treatment (without nitrogen) fertilised with sulphur in the sulphate form at a dose of ca. 60 kg S ha^{-1}, total nitrogen uptake by winter wheat was, on average for the study years, 68.6 kg N ha^{-1} and was by 2.6 kg N higher compared to the uptake in the control treatment without sulphur.

The increase in N uptake obtained by the authors of this study in the treatments with sulphur (-N+S), compared to sulphur-free ones, was found to be similar to that obtained for winter wheat by Fotyma (2003). The mentioned author conducted a six-year experiment on a similar soil (i.e. light clay belonging to medium soils with natural sulphur content) and obtained an increase in nitrogen uptake by 3 kg N ha^{-1} in the treatment with 50 kg S ha^{-1} applied in a form of potassium sulphate.

It should be added that Fotyma (2003) in experiments with spring wheat, grain maize and winter rapeseed, conducted under similar conditions as with winter wheat (at sulphur doses of 40, 50 and 80 kg S ha^{-1}), obtained an ambiguous result, i.e. a decrease or an increase in nitrogen uptake for treatment with sulphur of about 3 kg N ha^{-1} for wheat, or it increase by 3 kg N ha^{-1} for rapeseed and maize. Negative results for spring wheat may indicate overfertilization with sulphur as the sulphur requirement for this species is determined at 20–25 kg S ha^{-1}. In our study, no significant differences in nitrogen uptake were obtained for sulphur versus sulphur-free control treatments.

At precipitation rates of 620–640 (the first three periods of the study) and 425 mm (the last period of the study), the authors noted an increase in N uptake for treatments with sulphur compared to those not fertilized with this nutrient, with increasing nitrogen rates from 0 to 150 kg N ha^{-1} (every 30 kg N). Within rates 30–120 kg N ha^{-1}, it oscillated between 4–5 kg N ha^{-1}, but for the highest rate (150 kg N ha^{-1}) it deceased insignificantly to 0.4 kg N ha^{-1}.

Results slightly different from those presented here (especially for higher nitrogen dose) were obtained by Winiarski for winter wheat (unpublished materials, 2012) in a 4-year field research carried out on soil of the good wheat and very good rye complex at three experimental points in Poland. The results quoted above showed that for doses of 120 and 200 kg N ha^{-1}, N uptake from solid NS-type nitrogen fertilizer (urea-ammonium sulphate: 33% N, 12% S, with which 44 and 73 kg S ha^{-1} respectively were introduced), as compared to N fertilizers (urea, 46% N), increased by, respectively, 1 and 9 kg N ha^{-1}. Rusek et al. (2015) conducted a study with identical lengths of time and soil conditions with corn grown for green matter in which they applied rates of 150 and 230 kg N ha^{-1}. As a result, they obtained increased N uptake from the solid NS nitrogen fertilizer, relative to the N fertilizer, by respectively 2.5 and 4.3 kg N ha^{-1}. On the other hand, in a three-year study by Igras et al. (2012) under similar soil conditions for winter rapeseed cultivation with application rates of 160 and 240 kg N·ha^{-1}, an increased N uptake from solid nitrogen fertilizer type NS, as compared to urea N fertilizer (46% N), by 0.3 and 3.3 kg N ha^{-1} was obtained. The results cited above with maize and rapeseed correspond to those obtained by the authors of the presented paper.

The observed increase in N uptake under increasing dose of this component in fertilization confirms the results of studies by Klikocka et al. (2017) and Wang et al. (2010). Also, a detailed study by Kalembasa et al. (2015) showed that more total nitrogen (and from mineral fertilizer) was taken up by spring triticale fertilized with a dose of 150 kg N ha^{-1} than 30 kg N ha^{-1}. Also the percentage of nitrogen taken up from the fertilizer was higher after the application of 150 kg N ha^{-1}, compared to a dose of 30 kg N ha^{-1}.

An additional contribution to the discussion are results obtained by Salvagiotti et al. (2009), according to which N uptake by wheat was affected by both nitrogen fertilization up to 80 kg N ha^{-1} as well as sulphur fertilisation at a rate of 30 kg S ha^{-1}. In this case, averaging our own results showed increasing N uptake for both higher N rates (in the 90–150 range kg N ha^{-1}) as well as the applied dose of S.

In our study with winter wheat no significant differences in nitrogen uptake were obtained for fertilizer treatments with sulphur compared with those without. Similar results in studies with this crop were obtained by Fotyma (2004), while different and statistically significant results were obtained in experiments with winter rapeseed. In this case, the justification for significant statistical differences could be a higher requirement of rapeseed for sulphur fertilization, determined at the level of 50–60 kg S ha^{-1}.

In our study it was found that with increasing nitrogen dose, the efficiency of its utilization for treatments with sulphur compared to the control (without sulphur) showed a decreasing tendency, which means that the highest efficiency difference (17.8%) was obtained for the lowest N dose (30 kg N ha^{-1}), while the lowest (2.9%) for the highest dose (150 kg N ha^{-1}).

Fotyma's (2003) experiments with winter wheat, within identical N doses and data reference method, showed that nitrogen use efficiency, although lower than the author's, showed a similar increasing decreasing trend and amounted for the lowest dose to 8.5%, while for the highest N dose (150 kg N ha^{-1}) – only 2.5%. It should be added that in this case an increasing trend was recorded only for the first cycle of crop rotation. On the other hand, for spring wheat, an upward trend in the efficiency of nitrogen utilization with increasing N dose was observed, up to about 7% in both rotations but opposite to the studies presented in this paper.

Research results obtained by Winiarski (unpublished materials) report an in plus (upward) trend in nitrogen use efficiency with increasing nitrogen dose for sulphur versus sulphur-free treatments. For winter wheat, this efficiency increased from 0.9 to 4.5%, respectively, for nitrogen rates from 120 to 200 kg N ha^{-1} while in winter rapeseed it grew from 0.2 to 1.4% along with an increase in N dose from 160 to 240 kg N ha^{-1}. In contrast, Rusek et al. (2015) who cultivated maize for green matter, found that as the increase of application rate from 150 to 230 kg N ha^{-1}, brought a downward trend in nitrogen use efficiency. These efficiencies were 4.31 and 0.96%, respectively.

In this study, it was found that the agricultural efficiency of nitrogen (A_{NE}) amounted from 20.5 to 31.0 kg grain kg N, for treatments without sulphur. According to Tabak et al. (2020), for wheat crops, A_{NE} values typically range from 10 to 30 kg kg^{-1} N. Agricultural efficiency of nitrogen decreased with increasing rates of this nutrient and was the highest in the treatment fertilized with the lowest dose of 30 kg N ha^{-1}. This trend is consistent with the results of the study conducted by Fotyma (1999). However, it is different from the data obtained by Podleśna et al. (2018), in which an increase in the value of this indicator was found up to a dose of 60 kg N ha^{-1}, while for higher doses, it decreased. Authors of this paper obtained an increase in the agricultural efficiency of nitrogen for treatments additionally fertilized with sulphur with respect to sulphur-free treatments but only for its low doses, i.e. from 30 to 90 kg N ha^{-1} (respectively from 5.7 to 2.0 kg grain per 1 kg N).

Physiological efficiency index (P_{NE}) serves, in addition to the agricultural efficiency index (A_{NE}), to determine the ability of the plant to convert nitrogen into grain yield. In the discussed winter wheat experiment, the values of P_{NE} were higher than of A_{NE}, and decreased together with increasing nitrogen rates. Therefore, the highest physiological efficiency of nitrogen was found in the treatments with the lowest dose of nitrogen which is consistent with the results presented by Fotyma (1999). Also, the work of Szmigiel et al. (2016) showed that P_{NE} reached the highest values in the treatments fertilized with a dose of 60 kg N ha^{-1}, while doses of 120 and 150 kg N ha^{-1} caused its decrease. The applied sulphur fertilization in our study did not increase P_{NE} similarly to the study of Podleśna et al. (2018) with spring rye, where only a slight increase in these values was observed in treatments fertilized with doses of 60 and 90 kg N ha^{-1}. According to Salvagiotti et al. (2009), the value of physiological efficiency index is highly dependent on weather conditions. Thus, with their significant variation in years, N and S doses do not affect its magnitude.

In conclusion, the subject of this paper concerning the influence of sulphur fertilization on nitrogen uptake and utilization by winter wheat is rarely discussed in publications, probably because of low nutritional requirements of cereal plants for sulphur. Therefore, this study should be considered as a valuable piece of literature enriching the knowledge on this subject.

CONCLUSIONS

1. An increased N uptake was observed under the influence of applied sulphur fertilizers with increasing nitrogen doses.
2. Apparent nitrogen recovery (W_N) index by winter wheat within nitrogen doses was higher on sulphur-fertilized treatments compared to sulphur-free treatments (control). The application of sulphur fertilizers increased the utilization of applied nitrogen even at high doses of this nutrient. Higher utilization of fertilizer nitrogen reduces the risk of nitrogen loss and associated environmental hazards.
3. Sulphur fertilization caused an increase in the agricultural efficiency of fertilizer nitrogen – A_{NE} (18.4–8.0%) within its low ranges, i.e. from 30 to 90 kg N·ha^{-1}
4. Increasing nitrogen fertilization caused a decrease in the value of its physiological efficiency index (P_{NE}).

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