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Response of spring wheat to NPK and S fertilization. The content and uptake of macronutrients and the value of ionic ratios

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Abstract: The aim of the study was to evaluate the effect of nitrogen (N) and sulphur (S) fertilizers on the content and uptake of macronutrients by grain dry mass (DM) of spring wheat. A field experiment was conducted in south-eastern Poland on Cambisols (WRB 2007), in conditions of low S content in the soil. The experiment included 2 factors: fertilization with N (0, 40, 80, 120 kg ha⁻¹) and with S (0, 50 kg ha⁻¹).

The experiment showed a positive response of spring wheat to N and S fertilization. The highest grain yield was found after application of 80 kg N ha⁻¹ and addition of 50 kg S ha⁻¹ (5.43 t ha⁻¹). The described combination resulted in beneficial content of phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) (P –4.267, K–4.533, Mg–1.567, Ca–0.433 g kg⁻¹) and uptake of macroelements by grain dry mass (DM) (P–20.48, K–21.79, Mg–7.52, Ca–2.08 kg ha⁻¹). A generally positive correlation was found between content and uptake of macronutrients with exception of P content. Fertilization with N caused significantly narrowed mass ratios of K⁺: Ca²⁺, K⁺: Mg²⁺ and mass and mole ratio of K⁺:(Ca²⁺+Mg²⁺) and increased mass ratio of Ca:P. While S application narrowed significantly, mass ratios of K⁺:Ca²⁺ and K⁺: (Ca²⁺ + Mg²⁺) and increased mass ratio of Ca:P.

Keywords: nitrogen; sulphur; yield; macronutrient content in grain.

1 Introduction

During the last decade, cereal products have captured scientific and public attention as a basis of human nutrition and possible means to maintain and improve health. According to the food pyramid developed by the National Food and Nutrition Institute, low-processed cereal products are at the base of the pyramid and should be consumed as the most important source of minerals in the human diet. In Poland, cereal products meet about 50% of the daily requirement for these nutrients, especially potassium (K), phosphorus (P), magnesium (Mg), iron (Fe), zinc (Zn) and copper (Cu) [1].

Global cereal utilization in the 2016/17 season was 2007 million tonnes, of which wheat utilization was 732 million tonnes [2]. Total consumption of cereals for food is forecast to rise by 1.3% in 2017/2018, keeping pace with world population growth. This results in stable per capita consumption of 148 kg year⁻¹ for the world, as a whole, including wheat at 66.7 kg year⁻¹.

A noticeable problem in agriculture, in European countries and all over the world, is the deficiency of sulphur in arable soils due to the extreme tightening of environmental standards at the end of the last century [3]. Nitrogen and sulphur are important protein components and the correct N:S ratio significantly contributes to grain quality as well as to optimal yield of crop plants. Sulphur deficiency in crop production can cause serious economic and ecological problems. In the case of insufficient content of sulphur (and magnesium), the ‘law of the minimum’ may apply; while intensive nitrogen fertilization may lead to a reduction in its utilization by plants. This reduces the content of sulphur and its primary and secondary metabolites in the crop, which play an important role in the diet and health of animals and humans [4]. Sulphur application has been shown to increase total - N,

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Table 1: Sums of rainfall (mm) and mean air temperature (°C) in 2009-2011 and long-term averages from 1971-2005 (Zamość Research Station).

Years	Month (k)						Sum – Mean (III-VIII)		
	III	IV	V	VI	VII	VIII	K	p	t
2009	5.3	0.5	2.4	2.1	0.4	0.8	1.3	349.1	2652
2010	1.8	1.1	2.0	1.1	2.1	1.3	1.6	443.4	2715
2011	1.2	1.1	0.7	1.0	2.7	2.3	1.6	414.6	2581
1971-2005	5.1	1.8	1.5	1.6	1.7	1.0	1.6	367.4	2353

K - Selyaninov's hydrothermal coefficient [$K = (p \times 10) / (\sum t)$], p - precipitation (mm), t - temperature (°C).

P, K, Na, Ca and Mg in cereal grains [5]. Sulphur deficiency in soils in several parts of the world has led to the use of S fertilizer to enhance the production and quality of crops [6,7].

As yet, however, no further information is available about the influence of the sulphur (S) supplementation of nitrogen (N) fertilization on the content of macronutrients: phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) and the value of ionic ratios in grain of spring wheat. The importance and role of sulphur and nitrogen fertilization of spring wheat, grown on Cambisols (WRB 2007) with slightly acidic pH, classified as good rye complex, were the subject of the empirical study presented in this paper.

(between 28 March and 5 April, depending on the year) at a rate of 40.0 kg N ha⁻¹. In the combination of 80 and 120 kg N ha⁻¹ the second N application was made during BBCH 30-31; and in the object with 120 kg N ha⁻¹ the third N application was made during BBCH 55-59. First dose of sulphur, i.e. 40 kg S ha⁻¹, was applied before sowing in the form of kieserite - MgSO₄ × H₂O (as 15.1 % Mg, 20.0 % S), and the second dose, i.e. 10 kg S ha⁻¹, as foliar application in the form of magnesium sulphate heptahydrate (MgSO₄ × 7H₂O) (10.2% Mg, 12.8% S or 32% SO₃). Chemical protection against pests and disease was carried out according to the “Integrated method of winter and spring wheat production” [8].

2 Materials And Methods

2.1 Field experiments

A field experiment was carried out in 2009-2011 in Malice, south-eastern Poland (50°42' N, 23°15' E), in a randomized split-plot design (with four replications) on Cambisols (WRB 2007) consisting of light silty sand (sand 68%, silt 31%, clay 1%). The soil was slightly acidic (pH_{KCl} = 5.6), with high available P content (52.1 mg kg⁻¹; extracted by Double Lactate method, pH 3.6 (1:50 m/v ratio), medium content of K (84.5 mg kg⁻¹; extracted as P) and Mg (34.5 mg kg⁻¹; extracted by 0.0125 mol/L CaCl₂ (1:10 m/v ratio), and low S-SO₄ content (12.4 mg kg⁻¹; extracted by 0.025 m/L KCl).

The subject of the experiment was the Tybalt variety of spring wheat (*Triticum aestivum* L.) fertilized with different levels of N (0, 40, 80 and 120 kg N ha⁻¹) and S (0 and 50 kg S ha⁻¹). The area of each plot was 30 m² (5 m × 6 m). Phosphorus (P) (as 17.4% granular triple superphosphate) and potassium (K) (as 49.8% potassium chloride) fertilizers were applied before sowing at doses 39.6 and 83 kg ha⁻¹, respectively. The first application of N (as 34% ammonium nitrate) was also made before sowing

2.2 Meteorological conditions

The precipitation and air temperature during the growing season (March-August) in 2009-2011 are presented in Table 1. Selyaninov's hydrothermal coefficient (K) was calculated from meteorological data. Growing season in 2009 was classified as rather dry (1.3), while seasons 2010 and 2011 were optimal but on the border of wet (1.6).

2.3 Analysis and calculations

Grain yield (at 11% moisture content) was calculated after the wheat harvest performed at the phase BBCH 89-92. Chemical analyses of the grain (in 2009-2011) for the content of P, K, Mg and Ca were performed at the Agricultural Chemistry Station in Lublin, according to Accreditation Certificate of Testing Laboratory Nr AB 1186 and meets requirements of the PN-EN-ISO/IEC 17025-2005 standard. On the seeds from all the experiment variants, after mineralization in concentrated sulphuric acid, we assayed the content of: total phosphorus (P) based on the following reaction: ammonium heptamolybdate and potassium antimony(III) oxide tartrate react in an acidic medium with dialysed and diluted solutions of phosphate to form an antimony-phospho-molybdate complex.

This complex is reduced to an intensely blue-coloured complex by L(+) ascorbic acid – the complex is measured at 880 nm (Skalar SANplus flow analyser), potassium (K) and calcium (Ca) with flame photometry (Varian AA 240 FS), and magnesium (Mg) with Atomic Absorption Spectrometry (Varian AA 240 FS). The results facilitated the calculation of the following ionic (mass) ratios: $K^+:Ca^{2+}$, $K^+:Mg^{2+}$, $K^+:(Ca^{2+}+Mg^{2+})$, $Ca:P$, $Ca^{2+}:Mg^{2+}$ and mole ratios of $K^+:(Ca^{2+}+Mg^{2+})$.

Analysis of variance was performed by Snedecor's F-test. Significance of differences was calculated using Tukey's test ($p = 0.05$) followed by post-hoc analysis. The statistical software *Excel 7.0* and *Statistica* (StatSoft Polska 2010) were used for the analysis.

Ethical approval: The conducted research is not related to either human or animal use.

3 Results And Discussion

Analysis of the results showed a significant beneficial effect of N fertilizer on the grain yield of spring wheat and on content and uptake of K, Mg and Ca in grain dry mass (DM) with the exception of P. The addition of nitrogen in dose, 120 kg N ha⁻¹, significantly decreased P content in the grain. S fertilization also had a beneficial effect on the tested characteristics. No interaction was found between increasing application rates of N and S for yield or for the content and uptake of macroelements in grain dry mass (DM). However, the addition of sulphur to each dose of nitrogen applied independently, increased yield and the content and uptake of P, K, Mg and Ca in grain DM (Table 2). According to Klikocka and Głowacka [9] and Woźniak and Stępniewska [10], the amount of minerals uptake (macro- and micronutrients) depends on the crop species, variety, habitat conditions and agronomic factors.

The highest grain yield was found after application of 120 kg N ha⁻¹ (5.59 t ha⁻¹) although nitrogen in the dose of 80 kg ha⁻¹ (5.40 t ha⁻¹) caused a high yield, increased by 1.30 t ha⁻¹ (13.1%), in comparison to the control. The content of K, Mg and Ca in the spring wheat grain significantly increased in direct proportion to the increase in the N application rate and was the highest after application of 120 kg N ha⁻¹ (K – 4.550, Mg – 1.688, Ca – 0.458 g kg⁻¹ DM) (Table 2). The content of P in the spring wheat grain decreased in proportion to the increase of the N rate and was the smallest after application of 120 kg N ha⁻¹ (P – 4.067 g kg⁻¹ DM). The uptake of K, Mg and Ca by grain DM also significantly increased in direct proportion to the increase of the N dose and was the highest after application of 120

kg N ha⁻¹ (K – 22.55, Mg – 8.36 and Ca – 2.28 kg ha⁻¹). While the highest uptake of P by grain dry mass (DM) was found after application of 80 and 120 kg N ha⁻¹ (respectively P – 19.99 and 20.13 kg ha⁻¹) (Table 2).

The literature devotes much attention to the issue of N fertilization effect on grain yield and content of nutrients as well as its quality [11]. Generally, all applied nitrogen doses (40, 80, 120 kg N ha⁻¹), irrespective of S fertilizer, increased the content of most macronutrients, with the exception of phosphorus. Kozera et al. [4] reported that rate of 80 kg N ha⁻¹ favorably modified, in general, the mineral composition of the spring barley grain (especially the content of K, P and Mg), compared to control. Brzozowska [12] did not observe a significant effect of nitrogen fertilization on the content of macronutrients in the winter wheat grain, with the exception of nitrogen and potassium. According to Nogalska et al. [13], the variation in the amount of the elements taken by plants results from the size of the grain yield.

Fertilization with sulphur improved by 3.6% the effect of NPK on grain yield (Table 2). Spring wheat is considered as a species with low S requirements [14], however some researchers indicated a positive effect of S fertilization on cereal crop production [15,16]. Podleśna [17] found that S fertilization of winter wheat at a rate of 60 kg S ha⁻¹ led to a 11% increase of grain yield. According to Kozera et al. [4], it was a relatively high S dose, in comparison with to the recommendation for spring cereals in the countries of Western Europe: however, these authors took into consideration the low content of available sulfur in the soil and obtained high yield of grain. Research of Barczak and Nowak [5] and Klikocka and Głowacka [9] has shown that the use of S in elemental and sulphate forms promotes higher yield, improves the chemical composition of crops (increases macronutrient content in plants) and increases resistance to fungal and bacterial diseases.

The content of nutrients in the grain and their uptake after the application of S at a dose of 50 kg ha⁻¹ increased respectively by (%): P - 2.92; 6.33, K - 3.28; 7.01, Mg - 4.02; 7.76 and Ca -15.47; 18.01 in comparison with the control (Table 2). Whereas Barczak and Nowak [5] reported that sulfur applied to oat caused a slight decrease of the P, K and Ca content in the grain and increase of Mg content compared to the non-fertilized objects. In turn, Gondek and Gondek [18] did not identify significant differences in the content of Mg in the grain of wheat due to fertilization with NPK and S. Also, Skwierawska et al. [19] reported that fertilization with sulfur did not differentiate the content of P and K in the grain of spring barley.

Table 2: The influence of nitrogen and sulphur fertilization on content (g kg⁻¹) of macroelements in the spring wheat grain and their uptake (kg ha⁻¹).

Fertilization		Grain yield	P		K		Mg		Ca	
S	N	(t ha ⁻¹)	Content	Uptake	Content	Uptake	Content	Uptake	Content	Uptake
0S (N × S)	0	4.03 a	4.267 a	15.22 a	4.133 a	14.72 a	1.317 a	4.70 a	0.300 a	1.07 a
	40	5.15 a	4.167 a	15.30 a	4.267 a	15.66 a	1.483 a	5.45 a	0.367 a	1.35 a
	80	5.36 a	4.100 a	19.49 a	4.333 a	20.62 a	1.567 a	7.45 a	0.400 a	1.90 a
	120	5.47 a	4.033 a	19.51 a	4.433 a	21.45 a	1.610 a	7.79 a	0.433 a	2.10 a
50S (N × S)	0	4.13 a	4.383 a	16.02 a	4.200 a	15.33 a	1.417 a	5.18 a	0.400 a	1.46 a
	40	4.38 a	4.300 a	16.66 a	4.333 a	16.78 a	1.467 a	5.69 a	0.417 a	1.62 a
	80	5.43 a	4.267 a	20.48 a	4.533 a	21.79 a	1.567 a	7.52 a	0.433 a	2.08 a
	120	4.72 a	4.100 a	20.74 a	4.667 a	23.64 a	1.767 a	8.94 a	0.483 a	2.45 a
Mean (S)	0S	4.75 B	4.142 B	17.38 B	4.292 B	18.11 B	1.494 B	6.35 B	0.375 B	1.61 B
	50S	4.92 A	4.263 A	18.48 A	4.433 A	19.38 A	1.554 A	6.83 A	0.433 A	1.90 A
Mean (N)	0N	4.08 B	4.325 AB	15.62 B	4.167 D	15.03 D	1.367 D	4.94 D	0.350 D	1.27 D
	40N	4.27 AB	4.233 AB	15.98 B	4.300 C	16.22 C	1.475 C	5.57 C	0.392 C	1.49 C
	80N	5.40 A	4.183 AB	19.99 A	4.433 B	21.20 B	1.567 B	7.49 B	0.417 B	1.99 B
	120N	5.59 A	4.067 B	20.13 A	4.550 A	22.55 A	1.688 A	8.36 A	0.458 A	2.28 A
Mean (Y)	2009	4.74 B	4.213 A	17.66 A	4.675 A	19.73 A	1.519 A	6.45 AB	0.369 C	1.57 B
	2010	4.68 B	4.206 A	17.35 A	4.038 C	16.74 B	1.525 A	6.38 B	0.406 B	1.69 B
	2011	5.09 A	4.188 A	17.93 A	4.375 B	19.78 A	1.529 A	6.93 A	0.438 A	2.00 A

Values marked with different letters (A,B,C,D) in the column differ significantly ($P < 0.05$).

Analysis of the effect of S with increasing N application revealed that, despite the lack of statistically confirmed interactions, the most favourable values for the content and uptake of K, Mg and Ca by grain were found in the case of the combination of 80 and 120 kg N ha⁻¹ applied with 50 kg S ha⁻¹. Also, the content of P in grain decreased together with N doses but increased after application of S in relation to each dose of N (Table 2).

Interaction between nutrients in crop plants occurs when the supply of one nutrient affects the absorption and utilization of other nutrients. This type of interaction is most common when the concentration of one nutrient in the growth medium is excessive [20]. Nutrient interactions can occur at the root surface or within the plant, and can be classified into two major categories. In the first category are interactions occurring between ions because the ions are able to form a chemical bond. Interactions, in this case, are due to the formation of precipitates or complexes. The second form of interaction is between ions whose chemical properties are sufficiently similar that they compete for sites of adsorption, absorption, transport, and function on plant root surfaces or within plant tissues. Such interactions are more common between nutrients of similar size, charge, geometry of coordination and electronic configuration [20]. The anion-cation and anion-anion interactions occur mostly at the

membrane level and are primarily of a competitive nature. Upon addition of two nutrients, if the increase in crop yield and in nutrient concentration and nutrient uptake is greater than in the case of adding only one, the interaction is positive (synergistic) [21]. If adding the two nutrients together produces lower yield as compared to each of them alone, the interaction is negative (antagonistic). When there is no change, there is no interaction.

In the present study, the addition of sulphur to each level of nitrogen application independently increased yield and the content and uptake of P, K, Mg and Ca by grain dry mass (DM). This type of yield-increasing factor, in this case fertilizer, signals the additive effect of S. The additive interaction of the nutrients is generally manifested when there is a constant increase in weight (or yield) as a result of application of the second factor [22]. Assimilation of N and S in plants is closely associated [20]. Nitrogen nutrition has a strong regulatory influence on S assimilation, and vice versa. The ratio of N to S in proteins is regarded as a reliable indicator of sulphur supply in plants. Randall et al. [23] showed that the protein N:S ratio of wheat grain varied from 12 to 25 as a result of varying N and S supply.

Significant positive correlations were found between the wheat grain yield and the content and uptake of K, Mg and Ca by grain. According to Hiatt and Leggett [21],

Table 3: Correlation coefficients between grain yield and grain quality characteristics.

Features (n=24)	No	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Grain yield	(1)	-0.536	0.978	0.439	0.937	0.809	0.968	0.602	0.872
P - content	(2)	-	-0.348	-0.233	-0.509	-0.439	-0.522	-0.283	-0.458
P - uptake	(3)	-	-	0.421	0.911	0.787	0.945	0.592	0.850
K - content	(4)	-	-	-	0.721	0.456	0.467	0.280	0.421
K - uptake	(5)	-	-	-	-	0.793	0.923	0.583	0.840
Mg – content	(6)	-	-	-	-	-	0.928	0.698	0.839
Mg - uptake	(7)	-	-	-	-	-	-	0.670	0.902
Ca - content	(8)	-	-	-	-	-	-	-	0.910
Ca – uptake	(9)	-	-	-	-	-	-	-	-

Bold letters represent significant differences at $P 0.05 = 0.406$; $P 0.01 = 0.517$

a positive (synergistic) interaction occurs when, after fertilization with two nutrients, the increase in crop yield and in nutrient concentration and nutrient uptake is greater than in the case of adding only one. Contrary to Ca, Mg and K phosphorus is taken up by plants as an anion. P has a well-documented antagonistic interaction with Ca and Mg in soil due to chemical bonding with P, which precipitates are not very soluble, especially in alkaline soils. These precipitates can also occur within roots and other plant tissues, but the acidic biological environment allows for solubilisation more readily than with soil [24]. The study of Aulakh and Pasrich [25] showed negative interaction between S and P on grain yield. The authors suggested that sulphate and phosphate might compete for uptake and translocation pathways, affecting influx and movement of the nutrients by the plant. They also suggested that P may reduce the S availability in the soil and that high applications of P fertilizer could aggravate S deficiencies if S level in the soil is low.

The correlation coefficients between grain yield and the content of macroelements decreased in the order $Mg > Ca > K > P$. However, the strength of the relationship between grain yield and uptake of macroelements by grain DM had the following order $P > Mg > K > Ca$. Many authors have reported that plants with restricted growth (low yields) contain more nutrients per unit of plant mass in relation to plants growing more rapidly (high yields), irrespective of the nutrient content in the soil [26]. This is the concentration-dilution phenomenon. This phenomenon, however, was not confirmed in the present study.

A positive correlation between macronutrients with the exception of P was found in experiment. No significant

correlation was noted between the content of K and Ca, P and K and between P and Ca. While, the negative correlation was found between content of P and Mg, P and K as well as between uptake of Mg and Ca (Table 3).

The nitrogen fertilization significantly narrowed mass ratios of $K^+:Ca^{2+}$ and $K^+:Mg^{2+}$ as well as mass and mole ratio of $K^:(Ca^{2+}+Mg^{2+})$ and increased mass ratio of $Ca:P$; however, it did not influence on $Ca^{2+}:Mg^{2+}$ mass ratio. While, sulphur application significantly narrowed the mass ratios of $K^+:Ca^{2+}$ and $K^:(Ca^{2+}+Mg^{2+})$ and increased mass ratio of $Ca:P$. Application of sulphur did not effect on $K^+:Mg^{2+}$ and $Ca^{2+}:Mg^{2+}$ mass ratio and mole ratio of $K^:(Ca^{2+}+Mg^{2+})$ (Table 4). The value of macronutrients ratios is similar to that published by Kozera et al. [4]. According to Jankowska-Huflejt [27], the excess of potassium is more often reported in animal feed than its deficit. Maintaining the equilibrium between uni- and bivalent ions is facilitated by the higher content of calcium and magnesium which may be antagonistic to the potassium [28]. As was shown in this experiment, fertilization with N and S effected an increase of content and uptake in the grain of these both important nutrients. A comparison of the obtained results with the data reported by Jarnuszewski and Meller [28] and Wołoszyk and Iżewska [29] and for the spring barley grain, suggests that the mean values of $K^+:Ca^{2+}$ in the grain were too high, the ratio of $Ca^{2+}:Mg^{2+}$ and $Ca:P$ too low, whereas the ratios of $K^+:Mg^{2+}$ and $K^:(Ca^{2+}+Mg^{2+})$ can be considered as optimal. Interestingly, a significant widening of the values of the ionic ratios, especially $K^+:Mg^{2+}$ and $K^:(Ca^{2+}+Mg^{2+})$, occurred as a result of S application.

The content and uptake of macronutrients in wheat grain were, in the presented study, modified by the

Table 4: Ratios of macronutrients in the grain of spring wheat.

Fertilization S	N	K:Ca mass	K:Mg mass	K: (Ca+Mg) mass	mole	Ca:Mg mass	Ca:P mass
0S (N × S)	0	13.78 a	3.14 a	2.56 a	0.85 a	0.23 a	0.07 a
	40	11.63 b	2.88 a	2.31 bc	0.77 bc	0.25 a	0.09 a
	80	10.83 c	2.77 a	2.20 b	0.74 b	0.26 a	0.10 a
	120	10.24 c	2.75 a	2.17 c	0.73 c	0.27 a	0.11 a
50S (N × S)	0	10.50 c	2.96 a	2.31 b	0.78 bc	0.28 a	0.09 a
	40	10.39 c	2.95 a	2.30 b	0.78 bc	0.28 a	0.10 a
	80	10.47 c	2.89 a	2.27 b	0.76 bc	0.28 a	0.10 a
	120	9.66 d	2.64 a	2.07 c	0.70 cd	0.27 a	0.12 a
Mean (S)	0S	11.45 A	2.87 A	2.30 A	0.77 A	0.25 A	0.09 B
	50S	10.24 B	2.85 A	2.23 B	0.75 A	0.28 A	0.10 A
Mean (N)	0N	11.91 A	3.05 A	2.43 A	0.81 A	0.26 A	0.08 D
	40N	10.97 B	2.92 A	2.30 B	0.77 B	0.27 A	0.09 C
	80N	10.63 B	2.83 AB	2.23 B	0.75 BC	0.27 A	0.10 B
	120N	9.93 C	2.70 B	2.12 C	0.71 C	0.27 A	0.11 A
Mean (Y)	2009	12.67 A	3.08 A	2.48 A	0.83 A	0.24 A	0.09 B
	2010	9.95 B	2.65 A	2.09 C	0.70 C	0.27 A	0.10 A
	2011	9.99 B	2.86 A	2.22 B	0.75 B	0.29 A	0.10 A

Values marked with different letters (A,B,C,D) in the column differ significantly ($P < 0.05$).

weather. The exception was the content and uptake of P and content of Mg which were most favourable in the weather conditions of 2009 and 2011. The content and uptake of Ca were highest in 2011. The relationships described were confirmed in a study by Woźniak and Stępniewska [10]. Authors reported that high sums of precipitation facilitated the accumulation of phytate-P in grain, whereas precipitation shortages contributed to a greater accumulation of K and Mg in grain.

However, generally, the content and uptake of macroelements were the smallest in 2010. This year was characterized with a comparable K value to other years but also the highest amount of precipitation and the highest temperature, which were higher than the long-term means. This condition of long term precipitation could cause poor pollination of flowers because this process requires moderate dry and warm weather [30]. Large precipitation and high temperature cause good conditions for occurrence of fungal diseases [31]. High temperature during the generative phase of cereal development accelerates leaf aging and increases the respiration [30] that reduces photosynthesis and assimilation; and, in effect, causes poor seed filling. The weak plants have lower requirement in nutrients and probably the translocation of macronutrient from leaves and culms to the grain perturbed. The lowest macronutrients uptake by wheat cultivated in the 2010 year may indicate, also, that unfavourable weather conditions

occurred at least from shooting to the earing when uptake of nutrients and the growth processes are the most intensive [32]. These factors could negatively influence the wheat growth and grain development, and, as a consequence, plants gave the lowest grain yield irrespective on the N and S fertilization (Table 2).

4 Conclusions

The experiment showed that pre-sowing application of sulphur in the amount of 50 kg ha⁻¹ in combination with nitrogen fertilizer in the amount of 80 kg ha⁻¹ is sufficient to achieve optimal grain yield (5.43 t ha⁻¹) with beneficial uptake and content of P, K, Mg and Ca in grain. Obtained results confirmed that sulphur fertilization is necessary for effective plant cultivation. Supplementation of NPK fertilization with S, as demonstrated by our experiment, effectively improves the chemical composition of spring wheat grain. Hence, the addition of S to N fertilization of spring wheat can be recommended as a means of agronomic biofortification with macroelements (P, K, Mg and Ca) especially in areas with low soil S content. So, if one takes into account that mineral fertilization should be applied below the uptake level, the dose of 80 kg N ha⁻¹ with 50 kg S ha⁻¹ should be recommended for spring wheat cultivation in practice.

Conflict of interest: Authors state no conflict of interest.

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