J. Elem. s. 261–273 DOI: 10.5601/jelem.2011.16.2.10

EFFECT OF DIFFERENT SULFUR DOSES AND FORMS ON THE CONTENT OF SULFUR AND AVAILABLE POTASSIUM IN SOIL

Małgorzata Skwierawska

Chair of Agricultural Chemistry and Environmental Protection
University of Warmia and Mazury in Olsztyn

Abstract

High sulfur concentrations lead to soil acidification and, indirectly, to the mobilization of phytotoxic compounds, including aluminum and selected trace elements. On the other hand, sulfur deficiency decreases crop yield and quality. Previous studies investigating the effect of sulfur on the available potassium content of soil delivered inconclusive results.

The aim of this study has been to determine the effect of increasing doses of sulfate sulfur and elementary sulfur on the content of total sulfur, sulfate sulfur and available potassium in soil samples collected at a depth of 0-40 and 40-80 cm. A three-year field experiment was conducted on acid brown soil of the grain size distribution of heavy loamy sand. The soil was acidic in reaction ($pH_{1\ mol\ KCl\ dm^{-3}}$ of 5.30) and contained the following concentrations of mineral nutrients: mineral nitrogen – 24.0, sulfate sulfur – 4.10, available phosphorus – 34.5, available potassium – 110.0 mg kg^{-1} soil. Three sulfate sulfur ($S\text{-}SO_4$) and elementary sulfur ($S\text{-}S^0$) fertilization levels were applied each year: S_1 – 40, S_2 – 80 and S_3 – 120 kg ha^{-1}. In most cases, NPK+S fertilization, in particular the application of 120 kg S ha^{-1}, contributed to an increase in total sulfur concentrations in both sampled soil horizons compared with the NPK treatment. Sulfate accumulation in the soil increased over time, proportionally to the increasing rates of sulfur fertilizers. The effect of elementary sulfur application on an increase in the $S\text{-}SO_4$ content of the 0-40 cm soil layer was noted in the third year of the study. During the three-year experimental period, the application of both sulfur forms decreased the available potassium content of soil samples collected at the depth of 0-40 cm in comparison with the NPK treatment. The available potassium content of the 40-80 cm soil layer varied after sulfur fertilization. Sulfate sulfur exerted a stronger effect than elementary sulfur on available potassium levels in the soil.

Key words: fertilization, total sulfur, sulfate sulfur, elementary sulfur, available potassium, soil.

---

dr inż. Małgorzata Skwierawska, Chair of Agricultural Chemistry and Environmental Protection, University of Warmia and Mazury in Olsztyn, Oczapowskiego 8, 10-718 Olsztyn, e-mail: malgorzata.skwierawska@uwm.edu.pl

WPŁYW RÓŻNYCH DAWEK I FORM SIARKI NA ZAWARTOŚĆ JEJ FORM ORAZ POTASU PRZYSWAJALNEGO W GLEBIE

Abstrakt

Wysoka zawartość siarki w glebie powoduje jej zasiarczenie i zakwaszenie oraz pośrednio uruchamia związki fitotoksyczne, szczególnie glin i niektóre pierwiastki śladowe. Niewystarczające odżywianie roślin tym pierwiastkiem obniża plon i pogarsza jego jakość. Badania dotyczące wpływu siarki na zawartość potasu przyswajalnego w glebie są rozbieżne.

Celem badań była ocena wpływu nawożenia wzrastającymi dawkami siarki w formie siarczanowej i elementarnej na zawartość siarki ogółem, siarki siarczanowej oraz potasu przyswajalnego w poziomie gleby 0-40 i 40-80 cm. Trzyletnie doświadczenie polowe przeprowadzono na glebie brunatnej kwaśnej, o składzie granulometrycznym piasku gliniastego mocnego. Gleba przed założeniem doświadczenia charakteryzowała się odczynem kwaśnym (pH $_{1\ mol\ KCl\ dm^{-3}}$ wynosiło 5,30), zawartość składników mineralnych wynosiła: azot 24,0, siarka siarczanowa 4,10, fosfor przyswajalny 34,5 i potas 110,0 mg kg^{-1} gleby. Corocznie stosowano: S_1 – 40, S_2 – 80 i S_3 – 120 kg ha^{-1} siarki siarczanowej (S-SO_4) i elementarnej (S-S^0). Nawożenie NPK + S, szczególnie 120 kg S ha^{-1}, spowodowało na ogół wzrost zawartości siarki ogółem w obu poziomach gleby, w odniesieniu do obiektu NPK. Wraz ze wzrostem dawek siarki i upływem czasu trwania doświadczenia następowało nagromadzenie siarczanów w glebie. Wpływ nawożenia siarką elementarną na zwiększenie zawartości S-SO_4 w glebie, w poziomie 0-40 cm, uwidocznił się dopiero w trzecim roku. W okresie trzech lat trwania doświadczenia dodatek obu form siarki spowodował na ogół zmniejszenie zawartości potasu przyswajalnego w poziomie gleby 0-40 cm w porównaniu z obiektem NPK. Po nawożeniu siarką, w warstwie gleby 40-80 cm, zmiany zawartości potasu przyswajanego były nieregularne. Siarka siarczanowa oddziaływała silniej na zawartość potasu przyswajalnego niż forma elementarna.

Słowa kluczowe: nawożenie, siarka ogółem, siarka siarczanowa, siarka elementarna, potas przyswajalny, gleba.

INTRODUCTION

Both sulfur deficiency and excess can be harmful to plants (Terelak et al. 2001, Komarnisky et al. 2003). Recently, there has been a growing interest in sulfur fertilizers, mostly in non-industrialized areas distant from large urban agglomerations, where signs of plant sulfur deficiencies are particularly noticeable. The observed sulfur deficiency is associated with sulfur emission limits and a low sulfur content of mineral fertilizers (Mechteld et al. 2003, Walker, Dawson 2003). In Europe, sulfur deficiency occurs not only in plants with high sulfur requirements but is also frequently reported in cereals (Schung et al. 1993, Zhao et al. 1996, Scherer 2001).

Available potassium concentrations are considered to be low in nearly half of the total utilized agricultural area in Poland (Błaszczyk, Dudys 2000). Łabętowicz et al. (2005) observed negative potassium balance at 45% of the investigated farms. According to Lipiński (2005), potassium deficiency is one of the most common nutrient deficiencies in soils. Researchers differ in their opinions regarding the effect of sulfur on the available potassium content of soil. Motowicka-Terelak et al. (1995) reported that changes in available potassium levels in soil caused by excessive sulfur emissions are irregular and typical of the negative consequences of soil acidification. High sulfur concentrations in soil enhance potassium leaching (Murawska et al. 1999, Kiepul 1999). Krzywy et al. (2000) found that phosphogypsum fertilization increases the available potassium content of soil. According to Agrawal and Verma (1997), soil potassium availability reduces the adverse effect of sulfur on plant growth.

The aim of this study has been to determine the effect of increasing doses of sulfate sulfur and elementary sulfur on the content of total sulfur, sulfate sulfur and available potassium in soil samples collected at a depth of 0-40 and 40-80 cm.

MATERIALS AND METHODS

A three-year field experiment was conducted in Byszwałd near Lubawa, in 2000-2002, on acid brown soil of the grain size distribution of heavy loamy sand. The uppermost soil layer had $pH_{(KCl)}$ = 5.30 and contained the following concentrations of mineral nutrients: mineral nitrogen – 24.0, sulfate sulfur – 4.10, available phosphorus – 34.5, available potassium – 110.0 mg kg^{-1} soil. Three sulfate sulfur ($S\text{-}SO_4$) and elementary sulfur ($S\text{-}S^0$) fertilization levels were applied each year: S_1 – 40, S_2 – 80 and S_3 – 120 kg ha^{-1}. The experiment was carried out in a randomized block design and comprised eight fertilization treatments in four replications: 1) 0; 2) NPK; 3) NPK + $S_1\text{-}SO_4$; 4) NPK + $S_2\text{-}SO_4$; 5) NPK + $S_3\text{-}SO_4$; 6) NPK + $S_1\text{-}S^0$; 7) NPK + S_2 - S^0; 8) NPK + S_3 – S^0.

The following fertilizers were used: nitrogen – ammonium saltpeter or ammonium sulfate, phosphorus – triple superphosphate, potassium – 60% potash salt or potassium sulfate, sulfur – potassium sulfate + ammonium sulfate and elementary sulfur (Table 1). The tested crops were common cabbage (*Brassica oleracea var. capitata alba*) – medium late cv. Glory of Enkhuizen, onion (*Allium cepa var. cepa*) – cv. Wolska, and spring barley (*Hordeum sativum var. nutans*) – cv. Rodion.

Soil samples were collected in each plot, at a depth of 0-40 cm and 40-80 cm, before setting up the experiment, after harvest of each crop and prior to the sowing of the next crop. In the spring of 2001, soil samples were collected only from the 0-40 cm soil layer due to persistent precipitation. Air-dried soil samples were passed through a 1 mm mesh sieve. The content of total sulfur and sulfate sulfur was determined in soil samples by the turbidimetric method and available potassium concentrations were meas-

Table 1

Doses of NPK applied in the experiment

Plant	N	P	K
	(kg ha^{-1})		
Head cabbage	200.0	52.5	180.0
Common onion	160.0	60.0	183.0
Spring barley	90.0	80.0	111.0

ured by Egner-Riehm method. The results were verified statistically by an analysis of variance for two-factorial experiments in a randomized block design. Experimental factor *a* was a sulfur form and experimental factor *b* consisted of a sulfur dose. Regression analysis was performed using Statistica 6.0 PL software. The significance of differences between group means was determined by Duncan's test.

RESULTS AND DISCUSSION

Before setting up the experiment, the total sulfur content of soil was comparable across all experimental plots, in both sampled horizons (0-40 cm and 40-80 cm). Total sulfur concentrations were approximately 2.5-fold lower in the 40-80 cm soil layer than in the 0-40 cm layer. At the completion of the experiment, significant increase in the total sulfur content was noted in both soil horizons following the application of a single and triple dose of S-SO_4 and a double and triple dose of elementary sulfur, compared with the NPK treatment. In the remaining treatments, the total sulfur content of soil was similar to the values observed after NPK fertilization (Table 2). At the end of the experiment, in the treatments not fertilized with sulfur, the total sulfur content of soil decreased considerably (by around 16%) in the 0-40 cm layer but increased (from 11% to 36%) in the 40-80 cm horizon in comparison with the samples collected in the spring of 2000 (Table 2).

The S-SO_4 content of soil was affected by the dose and form of sulfur and the duration of the experiment. In most treatments, increasing sulfur doses contributed to an increase in the sulfate content of soil. Similar results were reported by Kulczycki (2003), who noted the highest concentrations of total sulfur and S-SO_4 in a treatment fertilized with the highest sulfur rate.

In the fall of 2000 and 2001 (after cabbage and onion harvest), following the application of single and double doses of sulfur, the S-SO_4 accumulation in both sampled soil horizons was similar to or lower than in the NPK treatment (Tables 3 and 4). The only exception was the double dose of

Table 2

Effect of different rates and forms of sulfur on the content of total sulfur in soil 0-40 cm and 40-80 cm (mg kg^{-1} soil)

Treatment	Before experiment	After experiment	cmBefore experiment	After experiment
	0 - 40 cm		40 - 80 cm	
0	54.6	45.6	19.9	24.4
NPK	54.8	45.6	20.2	22.5
NPK+ S_1-SO_4	58.2	50.3	22.8	31.6
NPK+ S_2-SO_4	57.9	45.2	20.9	20.5
NPK+ S_3-SO_4	53.6	57.6	23.2	48.6
NPK+S_1-S-^{0}	49.1	46.6	22.3	21.3
NPK+S_2-S-^{0}	58.5	51.7	24.0	25.7
NPK+S_3-S-^{0}	57.8	55.6	19.5	43.5
$LSD_{p\text{-}0.05}$				
a	n.s.	1.59	n.s.	1.06
b	n.s.	2.25	n.s.	1.50
a x *b*	n.s.	3.18	n.s.	2.12

SO_4 – sulfate sulfur; S^0 – elementary sulfur; S_1 – 40 kg ha^{-1}, S_2 – 80 kg ha^{-1}, S_3 – 120 kg ha^{-1}, *a* – form of sulfur; *b* – dose of sulfur; *a* x *b* interaction, n.s. – no significant difference

S-SO_4 applied in 2001, which increased the S-SO_4 content of the 0–40 cm soil layer. An increase in the sulfate content of soil, caused by the application of increasing sulfur doses, was reflected in the levels of sulfate sulfur and total sulfur in plants. At the completion of the study, the sulfate content of soil samples collected at the depth of 0-40 cm (Table 3) after the application of 40 kg ha^{-1} S-SO_4 and S-S^0 was similar to the level before setting up the experiment. Increasing sulfur doses considerably increased sulfur concentrations. In the 40-80 cm soil layer, the application of 40 kg S-SO_4 did not result in any S-SO_4 accumulation in the soil. The values noted in the remaining treatments were substantially higher (Table 4). This could have been due to a relatively low sulfur uptake by spring barley, as described by Skwierawska et al. (2008), and to the migration of sulfate sulfur from the uppermost soil layer, particularly after the application of increasing S-SO_4 doses. As demonstrated in a laboratory experiment performed by Zawartka and Skwierawska (2005), S-SO_4 ions are readily translocated downward and upward in the soil profile. Sulfate accumulation in both sampled soil horizons was considerably higher in the spring than in the fall of the preceding year, particularly after the application of S–S^0.

Sulfate accumulation in both sampled soil horizons was observed in the third year of the study in NPK+S treatments. It was dependent on a sulfur

Table 3

Effect of different rates and forms of sulfur on the content of sulfate sulfur in soil 0-40 cm (mg kg^{-1} soil)

Treatment	After cabbage harvest	Before onion sowing	After onion harvest	Before barley sowing	After barley harvest
0	0.9	2.3	0.9	2.1	1.60
NPK	0.0	2.3	1.1	2.0	1.10
NPK+ S_1-SO_4	0.0	5.1	1.6	2.3	5.30
NPK+ S_2-SO_4	0.0	6.3	3.2	2.6	9.70
NPK+ S_3-SO_4	9.8	6.2	3.6	4.2	12.5
NPK+S_1-S^{-0}	0.0	2.2	1.2	4.5	5.40
NPK+S_2-S^{-0}	0.0	2.6	1.5	8.4	9.60
NPK+S_3-S^{-0}	0.0	6.7	1.5	10.2	11.0
LSD-$_{p\text{-}0.05}$ *a* *b* *a* x *b*	 0.01 0.07 0.10	 0.20 0.28 0.39	 0.09 0.13 0.18	 0.35 0.49 0.69	 0.37 0.52 0.74

Explanations see Table 2

Table 4

Effect of different rates and forms of sulfur on the content of sulfate sulfur in soil 40-80 cm (mg kg^{-1} soil)

Treatment	After cabbage harvest	Before onion sowing	After onion harvest	Before barley sowing	After barley harvest
0	0.9	-	1.7	2.2	2.1
NPK	0.0	-	2.0	2.3	3.0
NPK+ S_1-SO_4	0.0	-	1.2	2.0	3.5
NPK+ S_2-SO_4	0.0	-	1.6	4.3	6.9
NPK+ S_3-SO_4	5.8	-	2.7	7.5	9.2
NPK+S_1-S^{-0}	0.0	-	1.9	3.3	5.3
NPK+S_2-S^{-0}	0.0	-	2.3	3.4	5.2
NPK+S_3-S^{-0}	0.0	-	4.0	6.7	7.3
LSD-$_{p\text{-}0.05}$ *a* *b* *a* x *b*	 0.06 0.09 0.12	-	 r.n. 0.39 0.55	 0.390 0.558 0.790	 0.25 0.35 0.49

Explanations see Table 2

dose, reaching the highest level after the application of 120 kg S. The effect of elementary sulfur on an increase in the S-SO_4 content of soil was not noted in the first and second year of the study; in the third year, the S-SO_4 concentrations in soil were comparable, regardless of the type of sulfur fertilizer. The above testifies to the gradual oxidation of elementary sulfur, observed also by WEN et al. (2001). Duncan's test revealed that the application of 80 kg and 120 kg S ha^{-1} over three years caused an increase in S-SO_4 accumulation in the soil in comparison with the NPK treatment and control (Table 5).

Table 5

Significance of differences in the content of sulfate sulfur in soil between particular objects according to Duncan's test. Differences statistically significant at ($p \leq 0.05$)

Treatment	0	NPK	I-S-SO_4	II-S-SO_4	III-S-SO_4	I-S-S0	II-S-S^0	III-S-S^0
0								
NPK	0.823871							
S_1-SO_4	0.352961	0.280555						
S_2-SO_4	0.003800*	0.002095*	0.042855*					
S_3-SO_4	0.000004*	0.000005*	0.000004*	0.000013*				
S_1-S^0	0.142091	0.104797	0.529193	0.138759	0.000004*			
S_2-S^0	0.006260*	0.003697*	0.059573	0.830541	0.000004*	0.174804		
S_3-S^0	0.000004*	0.000004*	0.000031*	0.028410*	0.010105*	0.000328*	0.021563*	
$\overline{x}$**	2.1091	1.9909	2.6023	3.7705	6.3000	2.9364	3.6568	4.9341

* significant difference,
** $\overline{x}$ – average content of sulfate sulfur in soil in particular objects for the years 2000-2003 (mg kg^{-1} soil)
SO_4 – sulfate sulfur, S^0 – elementary sulfur, S_1– 40 kg ha^{-1}, S_2 – 80 kg ha^{-1}, S_3 – 120 kg ha^{-1}

In the fall, after cabbage harvest, the available potassium content of soil samples collected at the depth of 0-40 cm ranged from 39.1 to 73.0 mg K kg^{-1} soil (Table 6). The potassium content of soil was significantly affected by the form and dose of sulfur. The application of increasing S-SO_4 doses, in particular 80 kg and 120 kg ha^{-1}, led to a decrease in available potassium concentrations compared with the NPK treatment and the treatments fertilized with elementary sulfur. In the first year of the experiment, elementary sulfur – due to its slow oxidation – had less pronounced influence on changes in the available potassium content of soil, which is consistent with the findings of JAGGI et al. (1999) and WEI ZHOU et al. (2002). The available potassium content of the 40-80 cm soil layer was substantially lower than in the uppermost soil layer in the same treatments, ranging between 38.1 and 67.1 mg K kg^{-1} soil (Table 7). Both the form and dose of sulfur had a significant effect on changes in available potassium concentrations in soil. In most cases, the application of sulfate sulfur and elementary sulfur contributed to a significant decrease in the potassium content of soil in comparison with the NPK treatment, except in the treatment fertilized with a single dose of elementary sulfur, where available potassium levels were comparable to those noted in the NPK treatment.

Soil samples collected in the spring of 2001 at the depth of 0-40 cm were characterized by a higher available potassium content than the samples analyzed in the fall (Table 6), which could have resulted from the mobilization of potassium reserves by precipitation. The applied sulfur doses caused irregular changes in the available potassium content of soil. A considerable decrease in potassium levels was observed only in the treatment fertilized with 120 kg ha^{-1} $S\text{-}S^0$. The 0-40 cm soil horizon contained larger quantities of available potassium than the soil samples collected before setting up the experiment and after the first year of the study.

Table 6

Effect of different rates and forms of sulfur on the content of available potassium in soil 0-40 cm (mg kg^{-1} soil)

Treatment	After cabbage harvest	Before onion sowing	After onion harvest	Before barley sowing	After barley harvest
0	39.1	40.8	33.6	44.6	14.2
NPK	73.0	67.6	117.7	92.3	102.1
NPK+ S_1-SO_4	67.6	86.2	95.8	81.8	106.6
NPK+ S_2-SO_4	52.6	68.0	68.6	75.7	107.1
NPK+ S_3-SO_4	52.6	70.0	43.6	76.9	64.1
NPK+S_1-$S\text{-}^0$	67.0	69.0	48.3	93.3	50.2
NPK+S_2-$S\text{-}^0$	69.1	74.6	55.0	59.5	99.6
NPK+S_3-$S\text{-}^0$	71.0	50.8	111.6	95.6	79.8
LSD-$_{p\text{-}0.05}$					
a	3.11	r.n.	3.52	3.28	3.98
b	4.40	4.64	4.98	4.64	5.63
a x *b*	6.23	6.56	7.04	6.56	7.96

Explanations see Table 2

In the fall, after onion harvest, the available potassium content of the 0-40 cm soil layer was in the range of 33.6-117.1 mg K kg^{-1} (Table 6). Sulfur fertilization caused a substantial decrease in potassium levels, compared with the NPK treatment, which could have been due to the leaching of potassium ions. Similar results were obtained by Zawartka and Skwierawska (2004, 2005) in laboratory experiments. In the treatment fertilized with 120 kg ha^{-1} elementary sulfur, available potassium levels were comparable with those noted in the NPK treatment. This indicates a slower release of elementary sulfur than sulfate sulfur, observed also by Kaczor, Brodowska (2008). The concentrations of available potassium in the 40-80 cm soil layer varied over a narrower range than in the 0-40 cm horizon, and they depended on the applied fertilizer (Table 7). S-SO_4 at a rate of 120 kg and elementary sulfur in all the doses decreased the available potassium content of soil in comparison with the NPK treatment. Increasing sulfur doses reduced the accumulation of available potassium in the 40-80 cm soil layer.

Table 7

Effect of different rates and forms of sulfur on the content of available potassium in soil 40-80 cm (mg kg^{-1} soil)

Treatment	After cabbage harvest	Before onion sowing	After onion harvest	Before barley sowing	After barley harvest
0	46.3	-	31.1	14.7	12.7
NPK	64.0	-	49.3	41.7	54.7
NPK+ S_1-SO_4	42.5	-	48.8	24.5	40.5
NPK+ S_2-SO_4	49.0	-	48.8	28.1	27.6
NPK+ S_3-SO_4	41.3	-	43.0	29.9	11.7
NPK+S_1-S^{-0}	67.1	-	45.8	31.8	24.3
NPK+S_2-S^{-0}	43.8	-	35.6	15.7	16.8
NPK+S_3-S^{-0}	38.1	-	33.6	21.3	13.2
LSD-$_{p\text{-}0.05}$ *a* *b* *a* x *b*	 2.39 3.39 4.79	 -	 1.42 2.01 2.84	 2.44 3.46 4.89	 2.48 3.51 4.96

Explanations see Table 2

In the spring, before barley sowing, the available potassium content of the 0-40 cm soil horizon was insignificantly higher than in the previous years (Table 6). The changes in potassium levels were random. Sulfur application decreased the potassium content of soil compared with the NPK treatment, except in the treatments fertilized with 40 and 120 kg elementary sulfur. Elementary sulfur, in comparison with sulfate sulfur, caused a significant increase in potassium concentrations in soil. Potassium levels were much lower in the 40-80 cm soil layer than in the 0-40 cm horizon (Table 7). The application of both sulfate sulfur and elementary sulfur (in particular a double dose of elementary sulfur) significantly reduced available potassium concentrations in the soil in comparison with the NPK treatment.

In the fall, after barley harvest, a considerable increase in the available potassium content of the 0-40 cm soil layer was noted in the treatments fertilized with 40 and 80 kg ha^{-1} sulfate sulfur and 80 kg elementary sulfur. The application of elementary sulfur caused irregular changes in potassium

Table 8

Significance of differences in the content of available potassium in soil between particular treatments according to Duncan's test. Differences statistically significant at $p \leq 0.05$

Treatment	0	NPK	I-S-SO_4	II-S-SO_4	III-S-SO_4	I-S-S^0	II-S-S^0	III-S-S^0
0								
NPK	0.000005*							
I-S-SO_4	0.000004*	0.249665						
II-S-SO_4	0.000071*	0.020458*	0.202487					
III-S-SO_4	0.005104*	0.000382*	0.015615*	0.211127				
I-S-S^0	0.000354*	0.007571*	0.109835	0.653441	0.378857			
II-S-S^0	0.000830*	0.003434*	0.066570	0.486041	0.519224	0.766755		
III-S-S^0	0.000116*	0.016446*	0.178949	0.877153	0.252962	0.743474	0.560684	
$\overline{x}$**	3.182	6.601	6.009	5.354	4.623	5.106	4.954	5.275

* significant difference,
** $\overline{x}$ – average content of sulfate sulfur in soil in particular objects for the years 2000-2003 (mg kg^{-1} soil),
SO_4 – sulfate sulfur, S^0 – elementary sulfur, S_1 – 40 kg ha^{-1}, S_2 – 80 kg ha^{-1}, S_3 – 120 kg ha^{-1}

levels. Sulfate sulfur, compared with elementary sulfur, contributed to a significant increase in potassium concentrations. Soil samples collected at the depth of 40-80 cm (Table 7) were characterized by a considerably lower available potassium content than those collected at the depth of 0-40 cm (Table 6). NPK+S fertilization, in particular the application of a triple dose of sulfate sulfur and elementary sulfur, significantly decreased available potassium levels compared with the control treatment.

During the three years of the experiment, application of either sulfur form led to a significant decrease in the available potassium content of the 0-40 cm soil layer in comparison with the NPK treatment (Table 6), except the treatments fertilized with a single dose of sulfate sulfur and a triple dose of elementary sulfur. Increasing doses of sulfate sulfur tended to decrease potassium levels while the application of elementary sulfur contributed to an increase in potassium concentrations. The application of both sulfur forms caused a decrease in the available potassium content of the 40-80 cm soil layer compared with the NPK treatment (Table 7). Increasing doses of sulfate sulfur and elementary sulfur (in particular the latter) reduced potassium concentrations in soil. The fluctuations in available potassium content could have been due to the acidifying effect of sulfur, also observed in our previous study (SKWIERAWSKA et al. 2006). As shown by the results of Duncan's test, the differences noted between the treatments over the three-year experimental period were statistically significant (Table 8). The average available potassium content of soil was the lowest in the treatment fertilized with a triple dose of sulfate sulfur (a statistically significant difference).

CONCLUSIONS

1. In most cases, NPK+S fertilization, in particular the application of 120 kg S ha^{-1}, contributed to an increase in total sulfur concentrations in both sampled soil horizons (0-40 and 40-80 cm) compared with the NPK treatment.

2. The application of sulfate sulfur caused an increase in the $S\text{-}SO_4$ content of the 0-40 cm soil layer as early as the first year of the study, while the effect of elementary sulfur was not noted until the third year. The above trend was not observed with respect to the 40-80 cm soil horizon. Sulfate accumulation in soil increased over time, proportionally to the increasing rates of sulfur fertilizers.

3. During the three years of the experiment, the application of both sulfur forms decreased the available potassium content of soil samples collected at the depth of 0-40 cm in comparison with the NPK treatment, whereas the available potassium content of the 40-80 cm soil layer varied.

4. Sulfate sulfur exerted a stronger effect on available potassium levels in soil than elementary sulfur.

REFERENCES

AGRAWAL M., VERMA M. 1997. *Amelioration of sulphur dioxide phytotoxicity in wheat cultivars by modyfying NPK nutrients*. J. Environ. Manag., 49:231-244.

BŁASZCZYK W.H., DUDYS K. 2000. *Zmiany odczynu i zasobności w magnez, potas oraz fosfor gleb brunatnych kwaśnych [Changes in soil reaction and fertility (Mg, K and P) in acid brown soils]*. Biul. Magnezol., 5(2): 77-83. (in Polish)

JAGGI R.,C., AULAKH M., S., SHARMA R. 1999. *Temperature effects on soil organic sulphur mineralization and elemental sulphur oxidation in subtropical soils of varying pH*. Nutrient Cycling Agroecosystems, 54(2): 175-182.

KACZOR A., BRODOWSKA M.S. 2008. *Yield of cocksfoot (Dactylis GlomerataL.) and its nitrogen and sulphur content after fertilization with various forms of these nutrients*. J. Elementol., 14(4): 665-670. (in Polish)

KIEPUL J. 1999. *After – Effect of simulated immission of sulphur and leming on leaching of some elements out of soil*. Rocz. AR w Poznaniu, 310: 59-65. (in Polish)

KOMARNISKY L.A., CHRISTOPHERSON R.J., BASU T.R. 2003. *Sulphur: its clinical and toxicologic aspects*. Nutrition, 19: 54-61.

KRZYWY E., JAKUBOWSKI W., PASIKOWSKI K. 2000. *Wpływ 7 hydratu siarczanu(VI) żelaza (II) i fosfogipsu stosowanych na tle różnych nawozów wieloskładnikowych na kształtowanie się w glebie form przyswajalnych fosforu i potasu oraz rozpuszczalnych w 1mol HCl siarki, kadmu, miedzi, niklu, ołowiu i cynk [The influence of iron (II) sulfate (VI) 7 hydrate and phosphogypsum on combination with different multi- component fertilizers soil available forms of phosphorus and potassium as well as 1 mol HCl soluble sulphur, cadmium, copper, nickel, lead and zinc]*. Fol. Univ. Stetin., 204 Agricultura, 81: 169-174. (in Polish)

KULCZYCKI G. 2003. *Wpływ nawożenia siarką na plon i skład chemiczny roślin oraz właściwości chemiczne gleby [Effect of sulphur fertilization on yield and chemical composition of crops and on the chemical properties of soil]*. Nawozy Nawożenie, 4(17):151-159. (in Polish)

ŁABĘTOWICZ J., MAJEWSKI E., KALWARA A., RUTKOWSKA B., SZULC W. 2005. *Bilans potasu w wybranych gospodarstwach rolniczych w Polsce [Potassium balance at some farms in Poland]*. J. Elementol.,10(4): 931-938. (in Polish)

LIPIŃSKI W. 2005. *Zasobność gleb Polski w potas przyswajalny [Abundance of Polish soils in available potassium]*. Nawozy Nawożenie, 2:55-60. (in Polish)

MCGRATH S.P. 1997. *Sulphur nutrition: An important factor for the quality of wheat and rapeseed*. Soil Sci. Plant Nutr., 43:1137-1142.

MOTOWICKA-TERELAK T., TERELAK H. 1995. *Potrzeby i skuteczność wapnowania gleb zasiarczonych [The need and success of liming of sulphur polluted soils]*. Zesz. Probl. Post. Nauk Rol., 418: 665-669. (n Polish)

MURAWSKA B., JANOWIAK J., SPYCHAJ-FABISIAK E. 1999. *Wpływ symulowanego kwaśnego deszczu i nawożenia azotowo-potasowego na wymywanie potasu z gleby [Effect of simulated acid rain and nitrogen and potassium fertilization on potassium leaching from soil]*. Zesz. Probl. Post. Nauk Rol., 467: 555-562. (in Polish)

SKWIERAWSKA M., ZAWADZKI B., ZAWARTKA L. 2006. *Wpływ różnych dawek i form siarki na zawartość magnezu w glebie i roślinach [Influence of different doses and forms of sulphur on magnesium content in soil and plants]*. J. Elementol., 11(4):495-506. (in Polish)

SKWIERAWSKA M., ZAWARTKA L., ZAWADZKI B. 2008. *The effect of different rates and forms of applied sulphur on nutrient composition of planted crops.* Plant Soil Environ., 54: 179-189.

TERELAK H., TUJAKA A., MOTOWICKA-TERELAK T. 2001. *Zawartość pierwiastków śladowych i siarki w glebach użytków rolnych województwa warmińsko-mazurskiego [Content of trace elements and sulphur in arable soils in the Province of Warmia and Mazury].* Zesz. Probl. Post. Nauk Rol., 476: 327-334. (in Polish)

WALKER K., DAWSON CH., 2003. *Sulphur fertilizer recommendations*. Nawozy Nawożenie, 3(16): 71-89. (in Polish)

WEI ZHOU, MIN WAN., PING LI, BAO LIN. 2002. *Oxidation of elemental sulfur in paddy soils as influenced by flooded condition and plant growth in pot experiment.* Biol. Fertil. Soils, 36: 352–358.

WEN G., SCHOENAU J.J., YAMAMOTO T., INOUE M., 2001. *A model of oxidation of an elemental sulfur fertilizer in soil.* Soil. Sci., 166:607-61.

ZAWARTKA L., SKWIERAWSKA M., 2004. *Wpływ nawozów wieloskładnikowych na wymywanie fosforu i innych makroelementów z gleby [Infuence of multicomponent fertilizers on the leaching of phosphorus and other macroelements from soil].* Pr. Nauk. AE Wrocław, 1017:69-77. (in Polish)

ZAWARTKA L., SKWIERAWSKA M., 2005. *Wpływ nawozów mineralnych zawierających siarkę na wymywanie makroelementów z gleby. [Infuence of mineral fertilizers containing sulphur on the leaching of macroelements from soil].* Zesz. Probl. Post. Nauk Rol., 505:523--529. (in Polish)

ZHAO F.J., HAWKESFORD M.J., WARRILOW A. G. S., MCGRATH S.P., CLARKSON D.T. 1996. *Responses of two wheat varieties to sulphur addition and diagnosis of sulphur dificiency*. Plant Soil, 81: 317-327.