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ORIGINAL PAPER

RESPONSE OF SPRING BARLEY TO NPK AND S FERTILISATION: YIELDING, THE CONTENT OF PROTEIN AND THE ACCUMULATION OF MINERAL NUTRIENTS*

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Abstract

Barley is a cereal of great importance in the crop structure both in Europe and globally. The nutritional value of barley grain is largely shaped by agronomic factors, in particular by fertilisation, which can have a significant impact on the content of individual elements and their quantitative interrelations in grain. The aim of the research was to evaluate yielding, the content of protein and the accumulation of mineral nutrients by the grain of spring barley grown exposed to varied NPK and S fertilisation. The study was based on a three-factor field experiment in a randomised split-plot design with 3 replications. The 1st order factor (A) was fertilisation with nitrogen (n = 3): N_1 – 40 kg ha^{-1}, N_2 – 80 kg ha^{-1}, N_3 – 120 kg ha^{-1}. The 2nd order factor (B) was fertilisation with phosphorus and potassium (n = 2): P_1K_1 – 30 kg P ha^{-1}, 80 kg K ha^{-1}; P_2K_2 – 45 kg P ha^{-1}, 120 kg K ha^{-1}. The 3rd order factor (C) was fertilisation with sulphur (n = 2): S_0 – 0 kg ha^{-1} and S_1 – 23 kg ha^{-1}. The study showed that the application of 80 and 120 kg N ha^{-1} resulted in obtaining a significantly higher grain yield of spring barley and, usually, a higher grain protein content than did the application of 40 kg N ha^{-1}. The increase in yield effected by sulphur fertilisation was significant in relation to the objects without sulphur fertilisation. The highest accumulation of nitrogen, phosphorus, potassium and magnesium was found following fertilisation with a dose of 80 kg N ha^{-1}, as compared with the accumulation with grain from the experimental variant with the application of 40 kg N ha^{-1}. As a result of sulphur application, considerably more nitrogen, phosphorus and potassium was obtained in the grain

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yield. Sulphur applied in combination with a dose of 120 kg N ha^{-1} usually caused a significant decrease in the accumulation of the tested macroelements.

Keywords: mineral nutrition, yield of grain, protein content, accumulation, macroelements.

INTRODUCTION

The primary goal of agriculture is the production of an adequate amount of food. This effect can be reached by the right selection of cultivars (Váňová et al. 2006), adequate cultivation practices as well as fertilisation (Gaj 2010, Nogalska et al. 2012). Plant fertilisation must be considered as a balanced system based on the budget of nutrients, considering their uptake by plants from soil and from fertilisers. A high yield-forming efficiency of fertiliser is possible provided that adequate proportions are maintained not only between the basic nutrients, such as nitrogen, phosphorus, potassium, calcium or magnesium, but also certain other elements, like sulphur, which has become a deficit element in the recent years, thus limiting the crop yield size and quality (Walker, Dawson 2003, Stern 2005, Szulc 2008).

According to Hitsuda et al. (2005), under sulphur deficit in soil, nitrogen from fertilisers does not show an optimal effect and its additional dose intensifies that deficit, diminishing yields and deteriorating their quality. In Poland, spring barley has a high share in the spring cereal crop structure. Grain of this type, allocated to both human consumption and animal feed production, must demonstrate parameters which mostly depend on plant fertilisation.

The aim of the study was to evaluate the effect of varied fertilisation with nitrogen, phosphorus, potassium and sulphur on the yielding, protein content and the accumulation of mineral nutrients by spring barley grain.

MATERIAL AND METHODS

Field experiments were performed over 2008-2010 at the Experiment Station of the Faculty of Agriculture and Biotechnology, the University of Science and Technology in Bydgoszcz, located in the northern part of Poland (53°16′N 17°47′E). The experiment was carried out in *Albic Luvisol* (LVa), formed from loam, representing the agronomic category of light soil, good rye complex, IIIb soil valuation class (WRB 2006). The soil showed a slightly acid reaction (pH_{KCl} 5.7), an average richness in available forms of phosphorus (65 mg kg^{-1} P), potassium (112 mg kg^{-1} K) and magnesium (49 mg kg^{-1} Mg). The content of sulphate (VI) form qualifies it to represent the soils with a low content of that nutrient (9.3 mg kg^{-1} $S\text{-}SO_4^{2-}$). The study was based on a three-factor field experiment in a randomised split-plot design with 3 replications in 20 m^2 plots.

The spring barley cultivar Antek was grown, preceded by winter wheat over the research years. The 1st order factor (A) was fertilisation with nitrogen (n = 3): N_1 – 40 kg ha^{-1} pre-sowing, N_2 – 80 kg ha^{-1} (60 kg ha^{-1} pre-sowing and 20 kg ha^{-1} as top-dressing), N_3 – 120 kg ha^{-1} (80 kg ha^{-1} pre-sowing and 40 kg ha^{-1} as top-dressing). The 2nd order factor (B) was fertilisation with phosphorus and potassium (n = 2): $P_1 K_1$ – 30 kg P ha^{-1}, 80 kg K ha^{-1}; P_2K_2 – 45 kg P ha^{-1}, 120 kg K ha^{-1}. The 3rd order factor (C) was fertilisation with sulphur (n = 2): S_0 – kg ha^{-1} and S_1 – 23 kg ha^{-1}. In the field experiment, nitrogen was applied pre-sowing in the form of ammonium sulphate and ammonium nitrate and as a top fertiliser, at the shooting phase (BBCH 30), in the form of ammonium nitrate. Phosphorus and potassium were applied pre-sowing in the form of triple superphosphate as well as potassium salt 60%.

The average air temperature during the plant growth, i.e March through July, was similar in respective years of the field experiment to the 60-year multi-year average – data from the Research Station in Mochełek (53°13′N 17°51′E) – Table 1.

Table 1

Temperature and rainfall distribution throughout the field experiment

Years	Months					Total or mean
	March	April	May	June	July	
Rainfall (mm)						
2008	61.2	38.7	11.5	15.5	58.7	185.6
2009	43.7	0.4	85.3	57.4	118.0	304.8
2010	28.6	33.8	92.6	18.1	107.4	280.5
1949-2010	24.7	27.3	43.1	54.3	71.3	220.7
Air temperature (°C)						
2008	3.0	7.6	13.2	17.6	19.2	12.1
2009	2.4	9.8	12.3	14.5	18.6	11.5
2010	2.4	7.8	11.5	16.7	21.6	12.0
1949-2010	1.8	7.4	13.0	16.2	18.0	11.3

The rainfall distribution in the spring-summer period varied demonstrably between the research years. Rainfall sums were much higher in 2009 and in 2010; the difference compared to the multi-year average (1949-2010) was 84.1 and 59.8 mm, respectively, which accounted for 38.1 and 27.1%. In 2008, the amount of precipitation was 35.1 mm lower than the mean value for that area. In May and June 2008, in April 2009 as well as in June 2010, the amount of precipitation was much lower than the multi-year average; the difference between the rainfall sum for those four months was: 31.6, 38.8, 26.9 as well as 36.2 mm, respectively. In March and May 2009, the amount of rainfall was almost twofold higher than the average for that area. In May 2010, the difference was 49.5 mm.

Immediately after harvest, the size of spring barley grain yield was determined. The following elements were determined in seeds from all the experimental treatments, after mineralisation in concentrated sulphuric acid: the content of total nitrogen based on the modified Berthelot reaction (Skalar SANplus flow analyser), total phosphorus – the method with ammonium molybdate (Skalar SANplus flow analyser), the content of potassium and calcium – with the method of flame photometry, and magnesium – with the method of Atomic Absorption Spectrometry. The results facilitated the calculation of the protein content (6.25 x N_{Total}). The accumulation of nutrients by the grain yield collected was calculated as the product of dry weight and the content of N, P, K, Ca and Mg.

The research results were statistically verified with the analysis of variance, as a three-factor design, and the differences between means were evaluated with the Tukey's test at the level of significance of $p < 0.05$. In order to determine the relations and dependences between the characteristics, values of the coefficients of linear correlation for treatment means were calculated.

RESULTS AND DISCUSSION

Mineral fertilisation showed a significant effect on the spring barley yield, the average value of which was 3.52 t ha^{-1} (Table 2). According to Klikocka et al. (2014), it is one of the key factors affecting the amount of the grain collected per unit area. The yields reported in the first and third years of research were lower than the yield collected in the second year and they

Table 2

Grain yield (t ha^{-1})

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	3.15	3.23	3.19	3.72	3.57	3.65	3.44	3.40	3.42
	N_2	3.49	3.35	3.42	3.69	3.71	3.70	3.59	3.53	3.56
	N_3	3.67	3.63	3.65	3.39	3.64	3.51	3.53	3.64	3.58
	mean	3.44	3.40	3.42	3.60	3.64	3.62	3.52	3.52	3.52
A = 0.099, B = n.s., C = 0,067; Interaction: B/A = n.s., A/B = n.s., C/A = 0.117, A/C = 0.140, C/B = n.s., B/C = n.s.										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

were: 2.64, 3.72, as well as 4.21 t ha^{-1}, respectively. Such considerable differences were due to the uneven precipitation distribution in growing seasons, especially in 2008.

The highest mean grain yields were obtained following the application of 80 and 120 kg N ha^{-1}. The difference between these treatments (N_2 and N_3) and treatment N_1 (40 kg N ha^{-1}) was on average about 4.4%.

Nitrogen fertilisation is one of the most effective yield formation factors (Candráková et al. 2009, Jankovic et al. 2011). Together with other agrotechnical factors, it demonstrates a comprehensive effect on the yield level as well as on the quality characteristics of grain (Liszewski 2008, Valkama et al. 2013). A positive effect of nitrogen fertilisation on the barley grain yield, according to Noworolnik et al. (2014), is most often a result of increasing the number of spikes owing to improved plant tillering. This macroelement enhances the number of grains per spike, which also results in the yield increase. Excessively intensive fertilisation of barley with nitrogen poses a risk of lodging, a higher intensity of diseases as well as a subsequent decrease in the yield size and quality. It can also increase the losses of nutrients, thus increasing the environmental pollution. Hence, the optimisation of plant supply with nitrogen is essential (Muurinen et al. 2007, Peltonen-Sainio 2008, Shejbalová et al. 2014).

Supplementing mineral fertilisation with an additional nutrient, i.e. sulphur, enhanced the barley grain yield size. Following the application of this macroelement, the mean grain yield was significantly higher (by 5.8%) than that obtained in the object of the experiment without sulphur fertilisation.

The interaction between fertilisation with nitrogen and sulphur affecting the size of barley grain yield wass statistically confirmed. The highest grain yield was obtained in object N_2S_1 (3.70 t ha^{-1}) – a significant difference as compared with the object receiving the same dose of nitrogen but without sulphur (N_2S_0), which was on average 8.2%. Even a greater difference in the volume of grain yield was found between the variants N_1S_1 and N_1S_0 – 14.4%. A significant decrease in the grain yield in the objects of the experiment with the highest doses of nitrogen and sulphur (N_3S_1) is notable as compared with the objects where lower doses of these elements were applied (40 and 80 kg N ha^{-1} + 23 kg S ha^{-1}). The differences equalled 3.8 and 5.1%, respectively.

Spring barley is considered to be a species with low sulphur requirements (Lipiński et al. 2003), although some researchers (Zhao et al. 2006, Järvan et al. 2008) indicate a positive effect of sulphur fertilisation on cereal crop production. As reported by Barczak (2010), the maximum barley grain yield was recorded after the application of about 40 kg S ha^{-1}. It is a relatively high dose compared with the ones recommended for spring cereal in the countries of Western Europe (Morris 2007), which the author attributes to the soil where the research was performed being poor in available sulphur and to the relatively high grain yield recorded.

In Great Britain and Germany, according to ZHAO et al. (2003), an increase in the spring barley grain yield following sulphur fertilisation at doses up to 30 kg S ha^{-1} fell within the range of 5-28% and 11-22%, respectively. In the present research, the grain yield increase as a result of sulphur application accounted for about 6% on average.

The fertilisation applied significantly modified the content of total protein in spring barley grain (Table 3). The highest mean protein contents were

Table 3

Protein content (g kg^{-1} d.m.)

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	104.7	107.2	106,0	105.5	104.5	105.0	105.1	105.9	105.5
	N_2	105.1	106.9	106.0	108.2	106.3	107.3	106.7	106.6	106.6
	N_3	108.3	108.3	108.3	107.8	106.7	107.3	108.0	107.5	107.8
	mean	106.0	107.5	106.7	107.2	105.8	106.5	106.6	106.7	106.6
A = 1.931, B = n.s., C = n.s.; Interaction: B/A = n.s., A/B = n.s., C/A = n.s., A/C = n.s., C/B = 1.329, B/C = 1.329.										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

recorded in 2008 and in 2010; they were significantly higher than the protein content in 2009; by 7.8 and 14.5%, respectively. According to LISZEWSKI et al. (2011), an increase in the content of total protein in barley grain, besides fertilisation, can be affected by semi-drought periods which occur during the vegetation period. Precipitation deficit before heading, at the grain filling stage and milk maturity, enhances an increase in the content of protein in the dry weight. In 2008 and in 2010, during grain filling (in June), the total precipitation was threefold lower as compared with the multi-year period for those months.

The mean content of total protein in spring barley grain from three research years was 106.6 g kg^{-1}. Similarly as reported by ZBROSZCZYK and NOWAK (2009), an increase in the nitrogen dose significantly differentiated the content of total protein in the grain of that species. The highest protein content, irrespective of the phosphorus and potassium fertilisation level, was recorded following the application of 120 kg N ha^{-1}. The difference in relation to the fertilisation dose of 40 kg N ha^{-1} was significant and accounted for 2.2%.

The study has not indicated the effect of varied doses of phosphorus, potassium and sulphur on the protein content in spring barley grain, although, based on the analysis of variance, a significant interaction of the above elements in modifying this yield quality trait has been proven. Sulphur applied with higher PK doses caused a statistically proven decrease in the grain protein content, which accounted for 1.5%, as compared with the experimental object without fertilisation. This decrease could have resulted from inadequate ratios of elements applied in fertilisation. Sulphur applied with lower PK doses caused a slight increase in the grain protein content in as compared with the objects where sulphur was not applied.

The role of sulphur mostly involves the stimulation of nitrogen transformations in the plant, especially protein biosynthesis (Dostálová et al. 2015). According to many authors (Potarzycki 2004, Ryant, Hřivna 2004, Jamal et al. 2010), the use of nitrogen from fertilisers by plants and its agricultural and physiological efficiency, especially following the application of high doses of this nutrient, are much higher under the conditions of a good plant supply with sulphur. In the present research, the effect of sulphur on protein biosynthesis was more favourable at lower PK doses. According to Liszewski (2008), the intensification of barley fertilisation is a factor enhancing an increase in the protein content in the grain.

The applied fertilisation significantly affected the accumulation of macroelements by spring barley grain. The highest nitrogen accumulation (Table 4)

Table 4

Accumulation of nitrogen (kg ha^{-1})

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	52.7	55.0	53.8	62.4	59.6	61.0	57.6	57.3	57.4
	N_2	58.8	57.2	58.0	63.1	63.1	63.1	60.9	60.2	60.6
	N_3	63.4	63.1	63.3	57.7	61.8	59.7	60.6	62.5	61.5
	mean	58.3	58.4	58.4	61.1	61.5	61.3	59.7	60.0	59.8
A = 2.001, B = n.s., C = 1.360; Interaction: B/A = n.s., A/B = n.s., C/A = 2.356, A/C = 2.831, C/B = n.s., B/C = n.s.										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

as affected by the application of this element was obtained following the dose of 120 kg N ha^{-1}. It was higher on average by about 7.0% than that following the application of 40 kg N ha^{-1}. Nitrogen accumulation by spring barley grain influenced by fertilisation with sulphur increased on average by about 5%, as compared with treatments without sulphur fertilisation.

The nitrogen availability to the plant is closely connected with its sulphur supply. According to Eriksen et al. (2001), when barley is well supplied with sulphur, 70% of the total nitrogen content is transported from leaves to spikes, however half of the sulphur deficit decreases the intensity of the process.

A marked effect was found of the fertilisation on the amount of phosphorus, potassium and magnesium taken up with the grain yield of spring barley (Tables 5, 6 and 7). Grain from the treatment with the application of 120 kg N ha^{-1} – similarly to the study by Tkaczyk (2002) – was characterised by significantly the highest accumulation of phosphorus, calcium (Table 8) and

Table 5

Accumulation of phosphorus (kg ha^{-1})

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	12.38	12.37	12.37	14.14	13.57	13.86	13.26	12.97	13.12
	N_2	14.01	13.08	13.55	13.90	15.43	14.66	13.96	14.26	14.11
	N_3	14.15	14.31	14.23	12.65	14.12	13.39	13.40	14.22	13.81
	mean	13.52	13.25	13.38	13.56	14.37	13.97	13.54	13.81	13.68
A = 0.476, B = n.s., C = 0.323; Interaction: B/A = 0.560, A/B = 0.673, C/A = 0.560, A/C = 0.673, C/B = 0.457, B/C = 0.457										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

Table 6

Accumulation of potassium (kg ha^{-1})

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	14.12	15.06	14.59	16.94	16.22	16.58	15.53	15.64	15.58
	N_2	16.29	17.58	16.94	16.76	17.74	17.25	16.52	17.66	17.09
	N_3	16.28	15.43	15.85	15.62	17.54	16.58	15.95	16.49	16.22
	mean	15.56	16.03	15.79	16.44	17.17	16.80	16.00	16.60	16.30
A = 0.789, B = 0.536, C = 0.536; Interaction: B/A = n.s., A/B = n.s., C/A = 0.929, A/C = 1.116, C/B = n.s., B/C = n.s.										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

Table 7

Accumulation of magnesium (kg ha^{-1})

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	4.69	5.06	4.87	5.50	5.40	5.45	5.09	5.23	5.16
	N_2	6.04	5.10	5.57	5.52	6.02	5.77	5.78	5.56	5.67
	N_3	6.05	5.69	5.87	5.23	5.39	5.31	5.64	5.54	5.59
	mean	5.59	5.28	5.44	5.42	5.61	5.51	5.50	5.44	5.47
A = 0.250, B = n.s., C = n.s.; Interaction: B/A = n.s., A/B = n.s., C/A = 0.294, A/C = 0.353, C/B = 0.240, B/C = 0.240										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

Table 8

Accumulation of calcium (kg ha^{-1})

Years	Nitrogen fertilisation	Sulphur fertilisation								
		S_0			S_1			mean		
		phosphorus and potassium fertilisation								
		P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean	P_1K_1	P_2K_2	mean
2008-2010	N_1	1.63	1.54	1.59	1.87	1.70	1.78	1.75	1.62	1.68
	N_2	1.83	1.60	1.71	1.74	1.73	1.73	1.78	1.66	1.72
	N_3	1.80	1.85	1.82	1.59	1.72	1.65	1.70	1.78	1.74
	mean	1.75	1.66	1.71	1.73	1.72	1.72	1.74	1.69	1.72
A = n.s., B = n.s., C = n.s.; Interaction: B/A = 0.100, A/B = 0.120, C/A = 0.100, A/C = 0.120, C/B = n.s., B/C = n.s.										

A – fertilisation with nitrogen
B – fertilisation with phosphorus and potassium
C – fertilisation with sulphur
n.s. – non-significant differences

magnesium of the experiment objects without sulphur – differences in comparison with fertilisation dose of 40 kg N ha^{-1} amounted to: 15.0, 14.5 and 20.5%, respectively. Phosphorus, potassium and magnesium accumulation in barley grain was the highest following the application of 80 kg N ha^{-1}. This results from the high yield-forming effectiveness of this dose (Table 2), which allowed obtaining grain yield similar to that following the application of 120 kg N ha^{-1}. It is well known that the curve presenting a relationship between grain yield and nitrogen dose in cereals is parabolic, with the clearly marked maximum. ZBROSZCZYK and NOWAK (2009), in an experiment on barley, showed that varied nitrogen doses demonstrated a significant effect only on the uptake of nitrogen and calcium. WILCZEWSKI (2014) found that the higher the nitrogen dose, the higher the content of phosphorus and potassium and the lower the content of magnesium in barley grain.

A significant increase in phosphorus and potassium accumulation by barley grain was observed in response to sulphur fertilisation – the respective differences as compared with the grain not fertilised with this element amounted to 4.4 and 6.4% (Tables 5, 6). This confirms a vital role of sulphur in shaping not only the yield size of spring barley grain but also its mineral composition. The relationships originate from the close connection between the yield size and the accumulation of nitrogen and other nutrients by the plant. According to the second degree regression model, estimated for spring barley grain based on three-research-year means, the maximum accumulation of potassium and magnesium reported for grain yield reached 3.69 and 3.81 t ha^{-1} respectively (Figure 1). Nitrogen and calcium accumulation as a function of the grain yield was linear.

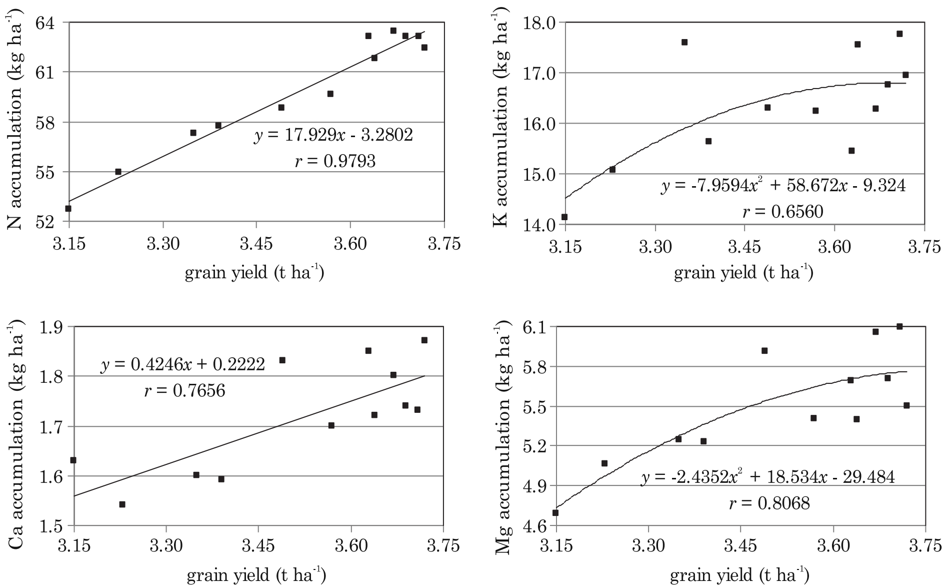

Fig. 1. Accumulation of macroelements in spring barley grain depending on the grain yield

CONCLUSIONS

1. Significantly higher grain yield and, usually, grain protein yield were obtained in spring barley following the application of 80 and 120 kg N ha^{-1}, as compared with the application of 40 kg N ha^{-1}. The increase in yield influ-

enced by sulphur fertilisation was significant in relation to the object without sulphur fertilisation.

2. The highest accumulation of nitrogen, phosphorus, potassium and magnesium was observed following the dose of 80 kg N ha $^{-1}$, as compared with the accumulation of these elements in grain from the experiment object with the application of 40 kg N ha^{-1}.

3. Application of sulphur resulted in obtaining considerably more nitrogen, phosphorus and potassium in grain yield. Sulphur applied in combination with a dose of 120 kg N ha^{-1} usually caused a significant decrease in the accumulation of the tested macroelements.

4. In view of the positive effect of sulphur on spring barley yield size and the accumulation of most of the tested mineral elements, as well as its favourable interactions with phosphorus and potassium in shaping the protein content of grain, it is recommended to consider this element in a cultivation technology for barley.

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