Agronomy Research **17**(X), xxx–ccc, 2019
https://doi.org/10.15159/AR.19.182

The effect of application of potassium, magnesium and sulphur on wheat and barley grain yield and protein content

L. Hlisnikovský[1,*], P. Čermák[1], E. Kunzová[1] and P. Barłóg[2]

[1]Department of nutrition management, Crop Research Institute, Drnovská 507, CZ16101 Prague 6, Ruzyně, Czech Republic
[2]Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznan University of Life Sciences, Wojska Polskiego 71F, PL60-625 Poznan, Poland
[*]Correspondence: l.hlisnik@vurv.cz

Abstract. The objective of our experiment was to study the effect of mineral fertilizers, rich mainly in the K, Mg and S content, and compare their effect on grain yield and protein content of winter wheat and winter barley with fertilizer treatments without these elements. The analyzed fertilizer treatments were 1) Control, 2) mineral nitrogen treatment (N), 3) mineral nitrogen with phosphorus (NP), 4) NP with potassium, magnesium, and sulphur (NP+KMgS), and 5) NP with magnesium, sulphur and minor part of manganese (4%) and zinc (1%) (NP+MgSMnZn). The experiment was established in Lukavec experimental station (the Czech Republic) in 2013 and lasted until 2017. The crop rotation consisted of four arable crops: winter wheat, winter barley, rapeseed, and potatoes, but only winter wheat and winter barley are analyzed in this paper (grain yields and crude protein content).
In comparison with the Control, the application of mineral fertilizers significantly increased grain yield and protein content of both kinds of cereal. Comparing mineral fertilizers, no significant differences were recorded between N, NP, NP+KMgS and NP+MgSMnZn treatments, showing that nitrogen was the most limiting factor affecting yield and protein content, and initial concentrations of K and Mg were suitable and capable to cover cereal's demands. However, application of fertilizers has increased the K and Mg soil content and thus prevents the soil from the element's deficiency, which does not has to be recognized in the early stages by visual observation of arable plants. The effect of the year was also significant as two out of four seasons were characterized by high temperatures and drought.

Key words: crude protein content, grain yield, *Hordeum vulgare* L., magnesium, mineral fertilizers, potassium, sulphur, *Triticum aestivum* L.

INTRODUCTION

Nitrogen is the key nutrient significantly influencing the affectivity of water utilization by plants as well as accumulation and shoot-root partitioning of photo-assimilates. Therefore, the nitrogen supply must be considered as a prime factor of crop production (Gonzalez-Dugo et al., 2010). However, it is well recognized that productivity of nitrogen fertilizers is related not only to its doses or chemical form but also to adequate relationships between nitrogen and other nutrients (Fageria, 2001). Phosphorus, potassium, and magnesium are, together with sulphur and calcium, the most important and principal plant macronutrients, directly influencing nitrogen uptake and utilization, and in this way the agriculture production.

The potassium is the most concentrated ion in the plant water tissue. The role of potassium is connected with physiological processes affecting the growth, development, and protein metabolism of arable plants, although it's not an integral part of any cellular organelle or structural part of the plant. According to Pettigrew (2008) the potassium is in plant involved in photosynthesis, assimilate transportation, enzyme activation and water management. Together with zinc, potassium plays a vital role in salt stress tolerance. It significantly minimize the NaCl-induced oxidative stress, enhance the photosynthetic pigment, counteract the adverse effect of salinity, enhance activity of antioxidant enzymes and increase root, shoot and spike length in wheat cultivars (Jan et al., 2017), while its deficiency significantly reduces the plant stature (Ebelhar & Varsa, 2000) and the number or the size of the leaves (Jordan-Meille & Pellerin, 2004). This reduction is then connected with decreased production of photosynthetic assimilates. The average consumption of potassium fertilizers has decreased significantly in the Czech Republic since the Velvet revolution in 1989, which is connected with the transition from socialism to capitalism, and is now approximately 13 kg ha^{-1} of arable land. The current average concentration of the potassium in the arable land of the Czech Republic is 253 mg kg^{-1} (2012–2017), 7.5% of arable land needs intensive fertilization and 28% of the land needs moderate fertilization (Smatanová & Sušil, 2018).

Magnesium is an essential element connected with activation of cellular enzymes, especially enzymes activating phosphorylation. Magnesium also plays a significant role in the signal transduction in the plant (Yu et al., 2011). The most crucial function of magnesium is in the formation of chlorophyll and thus plays an important role in the absorption of light energy required for photosynthesis. Acute magnesium deficiency can be recognized as chlorosis. Magnesium participating as the central atom of chlorophyll represents approximately one-fifth of all its plant content and is strongly bound to the chlorophyll. Thus, the chlorosis is a final demonstration of acute deficiency and low yields can be expected (Gransee & Führs, 2013). Deficiency of magnesium can occur because of low Mg contents in the source rocks forming the soil, because of losses from the soil by mobilization and leaching and because of inadequate agricultural practices (Gransee & Führs, 2013). The average concentration of magnesium in the Czech Republic is 194 mg kg^{-1} and the ratio of arable land with very low concentration is 15%, while high and very high concentrations were recorded on 17% of arable land (Smatanová & Sušil, 2018).

The sulphur is another essential element important for plant growth and structure elements. It is the main component of cysteine, methionine and several co-enzymes. The total sulphur uptake by winter wheat is usually 15–25 kg ha^{-1} under non-deficient situations (Zhao et al., 1999). Conventional fertilizer treatment with sulphur can increase the nitrogen content in the wheat organs and kernels, prolamin and total protein content in the kernels. On the other hand, the same treatment can also decrease the 1,000 grain kernels weight (Yang et al., 2007). Sulphur fertilization is also important for barley, as it positively modifies the hordein composition, increase malt extract and decrease malt hardness (Prystupa et al., 2018). The official statistical database of the Czech Republic does not analyze the consumption of fertilizers containing magnesium and sulphur. The deficiency of sulphur for arable crops was not considered as a problem during the second half of the 20th century as the energy industry supplied more than a sufficient amount of sulphur to the atmosphere and environment. The problem with sulphur as a limiting factor for crop production has been recognised when mechanisms of the cleaner production started to be implemented to the power plants in Europe. Another shortage of sulphur to the environment is connected with the replacement of ammonium sulphate with mineral fertilizers not containing sulphur. According to Ceccoti & Messick (1994) the share of ammonium sulphate dropped from 7.2% in 1973 to 3% in 1991. A significant decrease in the plant available sulphur was recorded in the last twenty years in the Czech Republic. The mean concentration of the sulphur in arable soil is approximately 15 mg kg^{-1} (51.1% of the arable land), which is evaluated as a low content. A suitable concentration of sulphur can be found only on 8.8% of the arable land (Smatanová & Sušil, 2018).

Concerning the roles of potassium, magnesium and sulphur in plants and the concentrations of these elements in the soil, we decided to analyze the effect of the application of fertilizers containing potassium, magnesium and sulphur to the most important cereals in the Czech Republic, wheat and barley, and analyze how these fertilizers affect their grain yield and protein content.

MATERIALS AND METHODS

Site description

The field trial was established in Lukavec experimental station (49°33.83347', E 14°59.38932', 625 m a.s.l.). The mean annual precipitation was 600 mm and the mean annual temperature was 7.0 °C in the spring of 2013, when the experiment was established. The type and kind of soil are sandy-loamy Cambisol. Basic chemical parameters of the soil at the beginning of the experiment show Table 1. The weather conditions (temperature and precipitation) of each season are presented in Fig. 1.

Table 1. Soil chemical properties in 2013. Soil reaction pH was measured in $CaCl_2$ solution and concentrations of plant available P, K, Ca, and Mg in soil samples were extracted by Mehlich III reagent and determined by ICP-OES

Soil depth	pH	P (mg kg^{-1})	K	Mg	Ca
0–15 cm					
Mean value	5.7	132	123	146	1,662
Assessment	slightly acid	high	suitable	suitable	suitable
15–30 cm					
Mean value	5.8	148	131	147	1,751
Assessment	slightly acid	high	suitable	suitable	suitable

Experimental design

The experiment consists of four fields, the area of one field is 1,568 m^2. Seven fertilizer treatments were evaluated in the experiment, but only five treatments are evaluated in this paper. The size of the experimental plot of one fertilizer treatment was 56 m^2 (7 x 8 m), including buffer strips to prevent the edge effect. The harvesting area for the purpose of the experiment was 24 m^2 (4 x 6 m) in the plot's central area. The crop rotation consisted of potato (var. Ditta), winter wheat (var. Mulan), rapeseed (var. Sharpa) and winter barley (var. Nero). The experiment was established in 2013 and each crop was grown for four consecutive seasons. The fertilizer treatments (with four replications on each field) were: 1) unfertilized Control, 2) mineral nitrogen – N, 3) mineral nitrogen with phosphorus – NP, 4) mineral NP with the addition of magnesium and sulphur (NP+KornKali) – NP+KMgS, and 5) mineral NP in combination with magnesium, sulphur and micronutrients (NP+Kieserite and EPSO Combitop) – NP+MgSMnZn.

The mineral nitrogen was applied as ammonium nitrate, phosphorus as diammonium phosphate, potassium as KornKali (40% K_2O, 6% MgO, 4% Na_2O and 12.5% SO_3). The Kieserite consists of 27% MgO and 55% of SO_3. The EPSO Combitop consists of 13% MgO, 34% SO_3, 4% of Mn and 1% of Zn.

The dose of nitrogen was 150 kg ha^{-1} for winter wheat and 100 kg ha^{-1} for winter barley. Phosphorus was applied at a dose of 50 kg ha^{-1} (P_2O_5) and potassium at a dose of 80 kg ha^{-1} (K_2O). Magnesium was applied at a dose of 12 kg ha^{-1} in the NP+KMgS treatment and 26 kg ha^{-1} in the NP+MgSMnZn treatment. The foliar application of EPSO Combitop (NP+MgSMnZn treatment) was done in three dressings (3 x 15 kg ha^{-1}) at the BBCH stages 15, 30 and 49. The cereal's straw was removed from the field after the harvest. The doses of applied mineral fertilizers and scheme of fertilizer application dressings are shown in Table 2 and 3.

Table 2. Doses of mineral nutrients (kg ha^{-1}) applied to the winter wheat and winter barley in the analyzed fertilizer treatments

Fertilizer treatment	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	MgO (kg ha^{-1})	SO_3 (kg ha^{-1})	Mn (kg ha^{-1})	Zn (kg ha^{-1})
Control	0	0	0	0	0	0	0
N	150 (100*)	0	0	0	0	0	0
NP	150 (100*)	50	0	0	0	0	0
NP+KMgS	150 (100*)	50	80	12	25	0	0
NP +MgSMnZn	150 (100*)	50	0	20 + 5.9	41 + 15.3	1.8	0.45

* – winter barley.

Table 3. Scheme of dressings of mineral fertilizers applied to the winter wheat and winter barley

Nutrients	Basal	1st dressing	2nd dressing	3rd dressing
N (ammonium nitrate)	15 kg N from DAP	The beginning of tillering (BBCH 21)-50%*	The phase of stem elongation (BBCH 30)-30%*	The phase of ear emergence (BBCH 51)-20%*
P_2O_5 (DAP)	Before sowing			
K_2O (KornKali)	Before sowing			
MgO (Kieserite)		Together with the first N app.		
MgO (EPSO Combitop 3 x 15 kg ha^{-1})		Autumn (BBCH 15)	The phase of stem elongation (BBCH 30)	The phase of early ear emergence (BBCH 49)

* – ratio of the applied nitrogen.

Analytical methods

The soil's value of pH was determined in the $CaCl_2$ solution, soil's available nutrients were determined according to the Mehlich III method, followed by ICP-OES analysis. Winter wheat and barley crude protein content was analyzed according to the Kjeldahl method (ČSN EN ISO 20483).

Data analysis

All statistical analyses were performed using STATISTICA 13.3 software (www.StatSoft.com). The effect of treatment, year and treatment*year was analyzed by one-way and factorial ANOVA. After obtaining significant ANOVA (MANOVA) results, the Tukey HSD post hoc test was applied to determine significant differences among individual treatments and years.

RESULTS AND DISSCUSSION

Soil analysis

The value of pH and the concentration of P, K, Ca and Mg (mg kg^{-1}) in the soil at the end of the experiment (2017) show Table 4. The table shows two pH values and elements concentrations as the soil analyses were performed on each field following the harvest of winter wheat (WW) and winter barley (WB). The concentration of P decreased at the end of the experiment in all treatments. Concentrations of K and Mg slightly increased during the time, which could be a partial contribution of mineral fertilizers containing these elements. The concentration of Ca fluctuated over the fertilizer treatments. Unfortunately, the results of the concentration of S in the soil at the end of the experiment are not available.

Table 4. Soil chemical properties in 2017 (0–15 cm) after completing the field experiment

Fertilizer treatment	pH		P (mg kg^{-1})		K		Mg		Ca	
	WW*	WB**	WW	WB	WW	WB	WW	WB	WW	WB
Control	6.5	5.9	131	96	182	198	1,958	1,685	180	177
N	6.4	6.0	108	92	141	161	1,896	1,616	165	165
NP	6.1	6.0	129	111	188	175	1,726	1,577	151	165
NP+KMgS	6.0	5.8	106	119	213	191	1,642	1,373	151	147
NP+MgSMnZn	5.7	5.8	95	121	198	253	1,339	1,562	147	163

* – winter wheat; ** – winter barley.

Grain yield

The winter wheat GIY was significantly affected by fertilizer treatment ($p < 0.001$), conditions of the year ($p < 0.001$) and by treatment*year interaction ($p < 0.001$). According to MANOVA results, the fertilizer treatment was the major factor influencing GIY by 67%. Weather conditions of each year influenced GIY by 30% and treatment*year interaction by 3%. The lowest GIY were recorded in the Control (3.59 t ha^{-1}), while the highest in the NP (7.31 t ha^{-1}). Comparing the years, the lowest GIY were recorded in 2016 (5.82 t ha^{-1}), while the highest in 2017 (7.48 t ha^{-1}) (Table 5).

Table 5. Winter wheat grain yield (t ha^{-1}) as affected by fertilizer treatments and years (2014–2017)

Fertilizer treatments	GIY (t ha^{-1})				Mean treatments
	2014	2015	2016	2017	2014–2017
Control	2.87 ± 0.13^{Aa}	4.81 ± 0.11^{Ab}	3.16 ± 0.31^{Aa}	3.54 ± 0.16^{Aa}	3.59 ± 0.21^{A}
N	7.59 ± 0.21^{Ba}	7.15 ± 0.28^{Ba}	5.89 ± 0.16^{Bb}	7.79 ± 0.23^{Ba}	7.10 ± 0.22^{B}
NP	7.95 ± 0.27^{Bb}	6.90 ± 0.12^{Ba}	6.16 ± 0.17^{Ba}	8.21 ± 0.15^{Bb}	7.31 ± 0.23^{B}
NP+KMgS	7.54 ± 0.14^{Bbc}	6.64 ± 0.16^{Bab}	6.26 ± 0.34^{Ba}	8.03 ± 0.36^{Bc}	7.12 ± 0.22^{B}
NP+MgSMnZn	7.61 ± 0.10^{Bb}	6.82 ± 0.07^{Ba}	6.36 ± 0.18^{Ba}	8.24 ± 0.28^{Bb}	7.26 ± 0.20^{B}
Mean years	7.03 ± 0.33^{c}	6.59 ± 0.16^{b}	5.82 ± 0.23^{a}	7.48 ± 0.32^{d}	

Means with the standard errors of the mean (SEM) followed by the same letter (^{A} vertically, ^{a} horizontally) were not significantly different at 0.05 probability level.

The winter barley GIY was significantly affected by fertilizer treatment ($p < 0.001$), conditions of the year ($p < 0.001$) and by treatment*year interaction ($p < 0.01$). Winter barley GIY was mainly affected by weather conditions (56%), followed by fertilizer treatment (42%) and slightly by treatment*year interaction (2%). The lowest winter barley GIY was recorded in the Control (2.35 t ha^{-1}), while the highest in the NP+KMgS treatment (5.27 t ha^{-1}). Comparing the years, the lowest GIY were recorded in 2015 (3.69 t ha^{-1}), while the highest in 2017 (5.66 t ha^{-1}) (Table 6).

Table 6. Winter barley grain yield (t ha^{-1}) as affected by fertilizer treatments and years (2014–2017)

Fertilizer treatment	GIY (t ha^{-1})				Mean treatments
	2014	2015	2016	2017	2014–2017
Control	2.10 ± 0.16^{Aa}	2.10 ± 0.07^{Aa}	2.68 ± 0.10^{Ab}	2.53 ± 0.09^{Aab}	2.35 ± 0.08^{A}
N	4.05 ± 0.06^{Ba}	3.83 ± 0.56^{Ba}	5.50 ± 0.18^{Bb}	5.80 ± 0.16^{Bb}	4.79 ± 0.26^{B}
NP	$4.43 \pm 0.10B^{Cab}$	3.55 ± 0.33^{Ba}	5.50 ± 0.35^{Bbc}	5.83 ± 0.30^{Bc}	4.83 ± 0.27^{B}
NP+KMgS	4.88 ± 0.17^{Cab}	4.25 ± 0.32^{Ba}	5.83 ± 0.31^{Bbc}	6.13 ± 0.13^{Bc}	5.27 ± 0.22^{B}
NP+MgSMnZn	4.48 ± 0.14^{BCa}	3.75 ± 0.10^{Ba}	5.88 ± 0.19^{Bb}	6.20 ± 0.28^{Bb}	5.08 ± 0.27^{B}
Mean years	4.16 ± 0.18^{a}	3.69 ± 0.17^{a}	5.18 ± 0.22^{b}	5.66 ± 0.26^{b}	

Means with the standard errors of the mean (SEM) followed by the same letter (^{A} vertically, ^{a} horizontally) were not significantly different at 0.05 probability level.

Crude protein content

The winter wheat CPC was significantly affected by fertilizer treatment ($p < 0.001$), conditions of the year ($p < 0.001$) and slightly by treatment*year interaction ($p < 0.05$). Unlike the GIY, the CPC was mainly affected by conditions of the year (72%), then by fertilizer treatment (27%) and finally by treatment*year interaction (1%). The lowest CPC was recorded in the Control (7.97%), the highest in NP treatment (11.68%). Comparing the years, the lowest CPC was recorded in 2014 (9.45%), while the highest in 2015 (12.66%) (Table 7).

Table 7. Winter wheat crude protein content (%) as affected by fertilizer treatments and years (2014–2017)

Fertilizer treatment	CPC (%)				Mean treatments
	2014	2015	2016	2017	2014–2017
Control	7.38 ± 0.23^{Aa}	8.54 ± 0.15^{Aa}	7.48 ± 0.30^{Aa}	8.47 ± 0.44^{Aa}	7.97 ± 0.19^{A}
N	10.42 ± 1.04^{Bab}	13.30 ± 0.34^{Bc}	9.92 ± 0.17^{Ba}	12.95 ± 0.55^{Bbc}	11.65 ± 0.48^{B}
NP	10.40 ± 0.58^{Ba}	13.24 ± 0.42^{Bb}	9.88 ± 0.35^{Ba}	13.22 ± 0.09^{Bb}	11.68 ± 0.44^{B}
NP+KMgS	9.44 ± 0.31^{ABa}	13.50 ± 0.43^{Bb}	10.51 ± 0.31^{Ba}	12.22 ± 0.21^{Bb}	11.42 ± 0.43^{B}
NP+MgSMnZn	9.59 ± 0.22^{ABa}	13.19 ± 0.36^{Bb}	9.44 ± 0.35^{Ba}	12.39 ± 0.51^{Bb}	11.15 ± 0.46^{B}
Mean years	9.45 ± 0.24^{a}	12.66 ± 0.34^{c}	9.63 ± 0.20^{a}	12.07 ± 0.32^{b}	

Means with the standard errors of the mean (SEM) followed by the same letter (^{A} vertically, ^{a} horizontally) were not significantly different at 0.05 probability level.

The winter barley CPC was significantly affected by fertilizer treatment ($p < 0.001$) and weather conditions ($p < 0.001$). The effect of treatment*year interaction was not statistically significant ($p = 0.06$). The major factor influencing winter barley CPC was the year (75%), followed by fertilizer treatment (23%). The lowest CPC was recorded in the Control (8.64%), while the highest in the N treatment (10.17%). Comparing the years, the lowest CPC was recorded in 2016 (9.10%), while the highest in 2017 (10.76%) (Table 8).

Table 8. Winter barley crude protein content (%) as affected by fertilizer treatments and years (2014–2017)

Fertilizer treatment	CPC (%)				Mean treatments
	2014	2015	2016	2017	2014–2017
Control	9.04 ± 0.25^{Aa}	8.28 ± 0.18^{Aa}	8.21 ± 0.28^{Aa}	9.03 ± 0.29^{Aa}	8.64 ± 0.15^{A}
N	10.11 ± 0.13^{Ba}	9.57 ± 0.17^{Ba}	9.71 ± 0.15^{Ba}	11.30 ± 0.16^{Bb}	10.17 ± 0.19^{B}
NP	9.77 ± 0.31^{ABa}	9.40 ± 0.18^{Ba}	9.58 ± 0.19^{Ba}	11.14 ± 0.20^{Bb}	9.97 ± 0.20^{B}
NP+KMgS	9.51 ± 0.24^{ABa}	9.52 ± 0.31^{Ba}	8.93 ± 0.20^{ABa}	10.58 ± 0.23^{Bb}	9.64 ± 0.19^{B}
NP+MgSMnZn	10.26 ± 0.14^{Bbc}	9.72 ± 0.27^{Bab}	9.20 ± 0.13^{Ba}	10.99 ± 0.24^{Bc}	10.08 ± 0.19^{B}
Mean years	9.82 ± 0.11^{b}	9.41 ± 0.12^{ab}	9.10 ± 0.11^{a}	10.76 ± 0.16^{c}	

Means with the standard errors of the mean (SEM) followed by the same letter (^{A} vertically, ^{a} horizontally) were not significantly different at 0.05 probability level.

Weather conditions

The basic characteristic of weather conditions are shown in Fig. 1, a, b, c, d. Generally, the 2014/2015 and 2015/2016 seasons can be characterised as standard or normal seasons typical for the experimental site. In other words, no extreme conditions have occurred and grain yields and CPC were appropriate to the production area, also showing general unsuitability of the area for growing wheat selected for production of leavened bakery products, even with the application of mineral fertilizers at ordinary doses. On the other hand, the 2014/2015 and 2016/2017 seasons were a little bit unusual (Fig. 2, a). The 2014/2015 winter started as very warm, with average precipitation. The field was covered by snow only during the January and spring started quite early (at the beginning of March). The whole growing season is characterised by very low precipitation with no rainfalls from June till August and also by very high temperatures

(36 tropical days altogether). This lack of precipitation significantly and positively affected the winter wheat CPC with average content 12.66%. Interestingly, the GIY of winter wheat was not negatively affected, showing good accessibility of nitrogen during the grain filling period. The protein content is mostly affected by external factors (Johnson et al., 1985) and is inversely proportional to precipitation during the growing season (López-Bellido et al., 1998). According to Rharrabti et al. (2003) and Hlisnikovský et al. (2015) the dry seasons provide wheat grains with high protein content. On the other hand, a low CPC shall be expected during the seasons with abundant precipitation (Flagela et al., 2010; Gürsoy et al., 2010). The 2016/2017 season was characterised by dry autumn (September, October and November 2016) and winter wheat and barley have a problem to emerge. The start of 2017 was extremely cold with temperatures below -10 °C during the nights, but with snow cover during the whole month. The spring was very cold and with an abundance of precipitation, while summer was very hot and dry, affecting the CPC similarly to the season 2014/2015. As extreme conditions will occur often in the near future in Europe (Grillakis, 2019) the application of mineral fertilizers will be more important factor in securing soil's fertility and sustainable production.

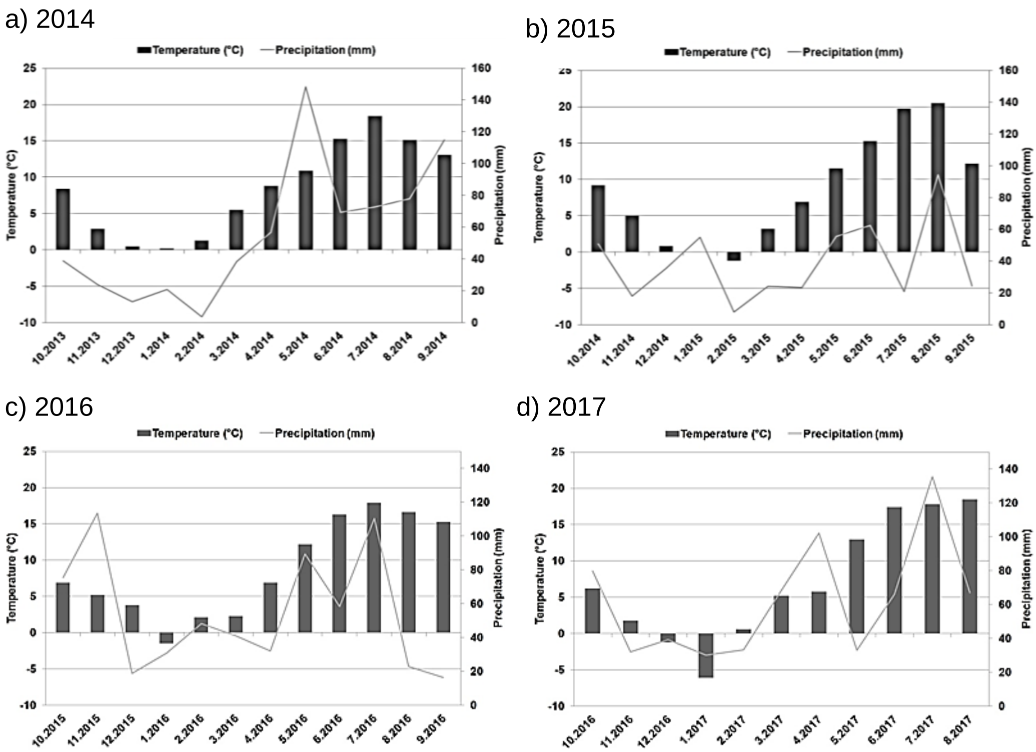

Figure 1. The average temperature (°C) and precipitation (mm) on the experimental site in a) 2014, b) 2015, c) 2016, and d) 2017 seasons.

Fertilizer treatments

According to the results, fertilizer treatment significantly influenced all analyzed parameters in both kinds of cereals, but the main message of this paper is that application of mineral fertilizers containing K, Mg and S (KornKali – NP+KMgS treatment and

Kieserit together with EPSO Combitop – NP+MgSMnZn treatment) provided over the whole time of the experiment GIY and CPC comparable with fertilizer treatments without these elements (N and NP treatments) (Tables 5, 6, 7, 8 and Fig. 2, b).

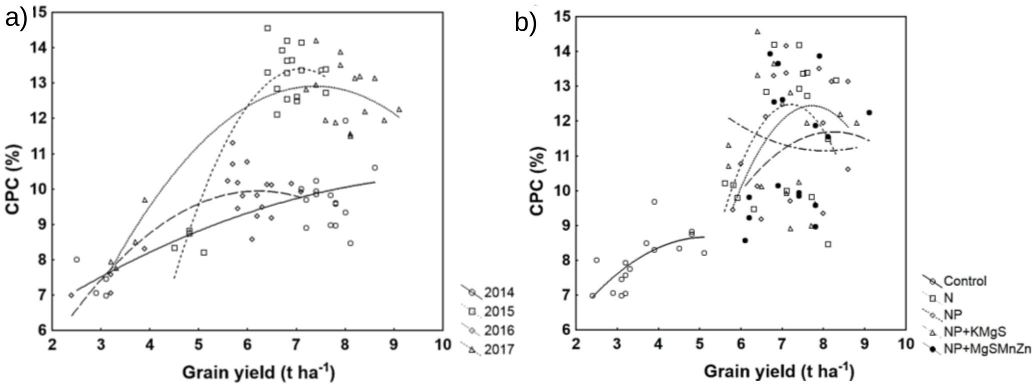

Figure 2. The effect of the a) years and b) fertilizer treatments on grain yield (t ha^{-1}) and CPC (%).

Nitrogen is the most important element for cereals, directly affecting chlorophyll content in leaves (Blandino et al., 2009) and key processes connected with solar-energy capture, moderating transformation and distribution of assimilates, thus influencing grain yields (Hejcman & Kunzová, 2010; Kunzová & Hejcman, 2010; Morell et al., 2011; Hejcman et al., 2012; Chen et al., 2018; Maresma et al., 2019) and protein content (Gooding et al., 2007; Hlisnikovský et al., 2015). It seems that nitrogen was the major contributor to the statistical differences recorded between the Control treatment and the rest of the analyzed fertilizer treatments in our experiment. According to Liebig's law of the minimum the growth and production of plants is not primarily dictated by total amount of the available nutrients, but by the important nutrient which is available in the smallest concentration. As the soil's concentrations of all important nutrients at the experimental site were evaluated as suitable (Table 1), the response of winter wheat and winter barley on fertilizers with K, Mg and S was neutral (without any positive effect in comparison with N and NP treatments).

Application of K increased the soil's concentration of this element (Table 4), which could be taken as a beneficial contribution of KornKali fertilizer. In comparison with the Control the grain yield and CPC were also significantly higher and winter barley grain yields were highest in the treatment with K. Though, no significant differences were recorded in comparison with N and NP treatments. This shows that both kinds of cereal were mainly limited by nitrogen availability and initial concentrations of K in the soil were sufficient for the production of high grain yields. Similar results were published by Hejcman & Kunzová (2010).

According to Grzebisz (2013) the positive reaction of cereals to magnesium fertilizers depends on many factors, such the initial concentration of the nutrient in the soil and the growth stage of cereals at the time of application. According to Matłosz (1992) the positive reaction of winter rye on the addition of magnesium was recorded only on soils with a low concentration of magnesium. Concerning the stage of growth, the best response of cereals on magnesium fertilization was connected with the application at the stage of heading (BBCH 51). The low level of Mg in the soil can have several reasons, as mentioned earlier. The non-visible deficiency is characterized by the decreased root system, directly influencing the performance of the plant and its yield and quality. The visible deficiency is expressed by chlorosis, particularly on older leaves, which has been not recorded on the experimental site. The chlorosis was not even recorded in the long-term fertilizer experiment established in 1955, located in the very same area (Hejcman & Kunzová 2010), where the concentration of Mg in the soil was 98 mg kg^{-1} (low) in the Control treatment after fifty years. And this is crucial for understanding the results we obtained. It can be supported that the positive reaction of cereals on Mg fertilization can be expected on soils with a low level of Mg (exchangeable or in the fixed pool). On the other hand, soils with sufficient concentration of Mg, whether it is based on the soil's origin rocks, or on the agronomical measures and practices, provide an adequate supply of this element and its added application don't have to directly affect, or improve, grain yield and grain quality. The regular application of Mg fertilizers maintains, or even increases, its soil concentration (Table 4) and thus prevent and protect the arable soil from the long-term depletion, which doesn't have to be recognized in the early stages. This was proved by the two-year pot experiment of Lošák et al. (2018), where the concentration of Mg and S linearly increased with the application rate of fertilizers. Our results are not as explicit as conditions in the field are more complex and non-space-limited in comparison with bounded pots, but the pattern can be recognized.

Application of sulphur was also not connected with any positive reaction from winter wheat and barley. Same results were published by Reneau Jr. et al. (1986), who suggested that atmospheric accretions of sulphur from nearby industry supplied a sufficient amount of sulphur during the season. Recently, however, industrial emissions have been significantly reduced and the crop yield depends more on the content of plant available form of sulphur in the soil then deposition from the atmosphere (Scherer, 2009). Salvagiotti & Miralles (2008) and Salvagiotti et al. (2009) documented that sulphur fertilization can positively influence nitrogen use efficiency with increasing doses of applied nitrogen, showing synergism between these two elements. That means that the effect of sulphur is without effect at low nitrogen rates and reveals the synergism with increasing nitrogen rates. That synergism was previously recorded by Reneau Jr. (1986). As we applied only one dose of nitrogen we cannot confirm such synergism. On the other hand, we also cannot confirm the positive effect of the addition of sulphur on grain yield and grain quality even when sulphur was applied together with high doses of nitrogen. This was kind of expected as cereals are crops not so dependent on sulphur in comparison with other arable crops, such as rapeseed or garlic. Probably the soil contained a sufficient amount of sulphur to nutrient requirements of both kinds of cereal.

In our study, we also applied manganese and zinc, together with magnesium and sulphur. Both elements are essential micronutrients involved in a wide variety of physiological processes (Barker & Eaton, 2015; Eaton, 2015). Foliar application of manganese can increase grain yield and protein content in winter wheat grain (Barlog & Grzebisz, 2008). However, the effect of its application depended on experimental sites, course of weather during growth seasons, growth stage, variety and soil pH. In general, manganese deficiency occurs on soils with pH above 6–6.5. In our study, the soil pH was below this value. Therefore. the plants were probably well supplied with this element. Peck et al. (2008) reported that foliar zinc application can also increase protein content and improve the protein composition in the wheat grain. The positive yield-forming effect of zinc, however, is manifested particularly under conditions of alkaline soils (Cakmak, 2008).

CONCLUSIONS

According to our results nitrogen was the limiting factor in the experiment and additional application of mineral fertilizers, containing K, Mg, S, and microelements, was not connected with a direct effect on grain yield and crude protein content of winter wheat and winter barley, as the initial content in the soil was suitable. However, application of these elements beneficially affected their soil's concentration (not analyzed in the case of S in our experiment, but proved by another papers), which is important as 26.3%, 7.5%, 15% and 50% of the arable land in the Czech Republic need intensive fertilization with P, K, Mg, and S, respectively. The regular application of these fertilizers can prevent the one-way deprivation of the soil, which doesn't have to be recognizable in the early stages.

ACKNOWLEDGEMENTS. The writing of the paper was supported by the Ministry of Agriculture of the Czech Republic by project MZE-RO0419 and by financial support of K+S KALI GmbH.

REFERENCES

Barker, A.V. & Eaton, T.E. 2015. Zinc. In: Handbook of Plant Nutrition. Ed. Barker, A.V. & Pilbeam, D.J., CRS Press, Boca Raton, London, New York, pp. 537–486.

Barłóg, P. & Grzebisz, W. 2008. Winter wheat yielding response to manganese foliar application and fungicide canopy protection. Fertilizers and Fertilization **32**, 18–31.

Blandino, M. & Reyneri, A. 2009. Effect of fungicide and foliar fertilizer application to winter wheat at anthesis on flag leaf senescence, grain yield, flour bread-making quality and DON contamination. *Eur. J. Agron*. **30**, 275–282.

Cakmak, I. 2008. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? *Plant Soil* **302**, 1–17.

Ceccoti, S.P. & Messick, D.L. 1994. Increasing plant nutrient sulphur use in the European fertilizer industry. *Agro. Food Ind. Hi Tec*. **5**, 9–14.

Chen, H., Deng, A., Zhang, W., Li, W., Qiao, Y., Yang, T., Zheng, Ch., Cao, Ch. & Chen, F. 2018. Long-term inorganic plus organic fertilization increases yield and yield stability of winter wheat. *The Crop Journal* **6**, 589–599.

Eaton, T.E. 2015. Manganese. In: Handbook of Plant Nutrition. Ed. Barker, A.V. & Pilbeam, D.J., CRS Press, Boca Raton, London, New York, pp. 427–486.

Ebelhar, S.A. & Varsa, E.C. 2000. Tillage and potassium placement effects on potassium utilization by corn and soybean. *Commun. Soil Sci. Plan*. **31**, 2367–2377.

Fageria, V.D. 2001. Nutrient interactions in crop plants. *J. Plant Nutr*. **2498**, 1269–1290.

Flagella, Z., Giuliani, M.M., Giuzio, L., Volpi, Ch. & Masci, S. 2010. Influence of water deficit on durum wheat storage protein composition and technological quality. *Eur. J. Agron*. **33**, 197–207.

Gonzalez-Dugo, V., Durand, J.L. & Gastal, F. 2010. Water deficit and nitrogen nutrition of crops. A review. *Agron. Sustain. Dev*. **30**, 529–544.

Gooding, M.J., Gregory, P.J., Ford, K.E. & Ruske, R.E. 2007. Recovery of nitrogen from different sources following applications to winter wheat at and after anthesis. *Field Crop Res*. **100**, 143–154.
Gransee, A. & Führs, H. 2013. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant Soil* **368**, 5–21.
Grillakis, M.G. 2019. Increase in severe and extreme soil moisture droughts for Europe under climate change. *Sci. Total Environ*. **660**, 1245–1255.
Grzebisz, W. 2013. Crop response to magnesium fertilization as affected by nitrogen supply. *Plant Soil* **368**, 23–39.
Gürsoy, S., Sessiz, A. & Malhi, S.S. 2010. Short-term effects of tillage and residue management following cotton on grain yield and quality of wheat. *Field Crop Res*. **119**, 260–268.
Grzebisz, W. 2013. Crop response to magnesium fertilization as affected by nitrogen supply. *Plant Soil* **368**, 23–39.
Hejcman, M., Kunzová, E. & Šrek, P. 2012. Sustainability of winter wheat production over 50 years of crop rotation and N, P and K fertilizer application on illimerized luvisol in the Czech Republic. *Field Crop Res*. **139**, 30–38.
Hejcman, M. & Kunzová, E. 2010. Sustainability of winter wheat production on sandy-loamy Cambisol in the Czech Republic: Results from a long-term fertilizer and crop rotation experiment. *Field Crop Res*. **115**, 191–199.
Hlisnikovský, L., Kunzová, E., Hejcman, M. & Dvořáček, V. 2015. Effect of fertilizer application, soil type, and year on yield and technological parameters of winter wheat (*Triticum aestivum*) in the Czech Republic. *Arch. Acker. Pfl. Boden.* **61**, 33–55.
Jan, A.U., Hadi, F., Midrarullah, Nawaz, M.A. & Rahman, K. 2017. Potassium and zinc increase tolerance to salt stress in wheat (*Triticum aestivum* L.). *Plant Physiol. Bioch.* **116**, 139–149.
Johnson, V.A., Mattern, P.J., Peterson, C.J. & Kuhr, S.L. 1985. Improvement of wheat protein by traditional breeding and genetic techniques. *Cereal Chem.* **62**, 350–355.
Jordan-Meille, L. & Pellerin, S. 2004. Leaf area establishment of maize (Zea Mays L.) field crop under potassium deficiency. *Plant Soil* **265**, 75–92.
Kunzová, E. & Hejcman, M. 2010. Yield development of winter wheat over 50 years of nitrogen, phosphorus and potassium application on greyic Phaeozem in the Czech Republic. *Eur. J. Agron*. **33**, 166–174.
López-Bellido, L., Fuentes, M., Castillo, J.E. & López-Garrido, F.J. 1998. Effects of tillage, crop rotation and nitrogen fertilization on wheat-grain quality grown under rainfed Mediterranean conditions. *Field Crop Res*. **57**, 265–276.
Lošák, T., Elbl, J., Kintl, A., Čermák, P., Mühlbachová, G., Neugschwandtner, R.W., Torma, S. & Hlušek, J. 2018. Soil agrochemical changes after kieserite application into chernozem and its effect on yields of barley biomass. Agriculture (Poľnohospodárstvo) **64**, 183–188.
Maresma, Á., Martínez-Casasnovas, J.A., Santiveri, F. & Lloveras, J. 2019. Nitrogen management in double-annual cropping system (barley-maize) under irrigated Mediterranean environments. *Eur. J. Agron*. **103**, 98–107.
Matłosz, C. 1992. Effect of cereals fertilization with magnesium conducted in different stages of growth on yields of grain and straw and some grain quality parameters. PhD thesis. Poznań University of Life Sciences, Poznań, 47 pp. (in Polish). In: Grzebisz W. (2013): Crop response to magnesium fertilization as affected by nitrogen supply. *Plant Soil* **368**, 23–39.
Morell, F.J., Lampurlanés, J., Álvato-Fuentes, J. & Cantero-Martínez, C. 2011. Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization. *Soil Till Res.* **117**, 76–84.

Peck, A.W., McDonald, G.K. & Graham, R.D. 2008. Zinc nutrition influences the protein composition of flour in bread wheat (*Triticum aestivum* L.). *J. Cereal Sci.* **47**, 266–274.
Pettigrew, W.T. 2008. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. *Physiol. Plantarum* **133**, 670–681.
Prystupa, P., Peton, A., Pagano, E. & Gutierez Boem, F.H. 2018. Sulphur fertilization of barley crops improves malt extract and fermentability. *J. Cereal Sci.* **85**, 228–235.
Reneau Jr., R.B., Brann, D.E. & Donohue, S.J. 1986. Effect of sulphur on winter wheat grown in the coastal plain of Virginia. *Commun. Soil Sci. Plan.* **17**, 149–158.
Rharrabti, Y., Royo, C., Villegas, D., Aparicio, N. & García del Moral, L.F. 2003. Durum wheat quality in Mediterranean environments I. Quality expression under different zones, latitudes and water regimes across Spain. *Field Crop Res*. **80**, 123–131.
Salvagiotti, F. & Miralles, D.J. 2008. Radiation interception, biomass production and grain yield as affected by the interaction of nitrogen and sulfur fertilization in wheat. *Eur. J. Agron*. **28**, 282–290.
Salvagiotti, F., Castellarín, J.M., Miralles, D.J. & Pedrol, H.M. 2009. Sulfur fertilization improves nitrogen use efficiency in wheat by increasing nitrogen uptake. *Field Crop Res*. **113**, 170–177.
Scherer, H.W. 2009. Sulfur in soils. *J. Plant Nutr. Soil Sc.* **172**, 326–335.
Smatanová, M. & Sušil, A. 2018. The results of agro-chemical testing of arable soils between 2012–2017. Central Institute for Supervising and Testing in Agriculture (in Czech).
Yang, G., Zhao, G., Liu, L. & Yang, Y. 2007. Sulphur effect on protein components and grain yield of wheat. *Chinese Journal of Soil Science* **38**, 89–92.
Yu, L., Xu, L., Xu, M., Wan, B., Yu, L. & Huang, Q. 2011. Role of Mg^{2+} ions in protein kinase phosphorylation: insights from molecular dynamics simulations of ATP-kinase complexes. *Mol. Simulat.* **37**, 1143–1150.
Zhao, F.J., Hawkesford, M.J. & McGrath, S.P. 1999. Sulphur assimilation and effects on yield and quality of wheat. *J. Cereal Sci.* **30**, 1–17.