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Effect of fertilisation with P, Mg or S enriched urea-ammonium nitrate solution on the management of macronutrients in common maize

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Abstract: The purpose of this study has been to determine the effect of fertilisation with urea-ammonium nitrate (UAN) solution enriched with P, Mg or S on the content of macronutrients in the grain and straw of maize. The following fertilisers were tested in the field experiment: ammonium nitrate, urea, UAN – 32% N; RSM+S – 26% N + 3% S; RSM+P(Medium) – 26% N and 4.80% P; RSM+P(Starter) – 21% N and 7.86% P; UAN + Mg – 20% N + 4% Mg. In each year of the experiment, significant differentiation in the contents of P, K, Ca, Mg and S in maize grain and straw was observed, depending on the applied nitrogen fertilisation. However, considering the average values from each treatment achieved over the three years, it was demonstrated that the fertilisation significantly changed only the content of P and S in grain and K and Ca in straw of maize. The removal of nutrients was the highest in the second year of the research and amounted in kg·ha^{-1}: P – about 100, K – about 350, Ca – about 80, Mg – about 35 and S – about 31, which in turn were differentiated over the years of the experiment in the three years. The removal of P, K, Mg and S also significantly depended on fertilisation. Significant differences, however, most often concerned the control treatment relative to the fertilised ones. The contribution of grain to the accumulation of nutrients also varied significantly in the three years of the experiment. Significantly the lowest share of grain in terms of P and S accumulation was noted in maize grown without N fertilisation.

Keywords: calcium, content and uptake of phosphorus, magnesium and sulphur, magnesium and sulphur fertilisation, maize, nitrogen, phosphorus, potassium

INTRODUCTION

Maize is one of the three major cereals, considered to be important for food and feed security. In 2021, the total acreage of farmland cropped with maize in Poland was 1.70 mln ha, of which 50% were sown with maize grown for grain (ARMiR, no date).

The availability of nutrients in soil is a key factor influencing the content of nutrients in maize grain and maize yields (Ciampitti *et al.*, 2013; Dutta *et al.*, 2020). Maize responds well to NPK fertilisation, producing the highest biomass of all crops, alongside an increasing grain yield with a higher content of nutrients (Setiyono *et al.*, 2010). According to Stewart *et al.* (2005), balanced fertilisation (NPK Ca) resulted in a 57% increase in the grain yield of maize in 1960–2000.

Nitrogen fertilisation is one of the main factors that guarantee higher yields of crops (Zhu and Chen, 2002; Liang *et al.*, 2020). The yield of maize grain depends on the intensity of photosynthesis, but a nitrogen and other macronutrients (Mg, P, K and Ca) deficit tends to affect the intensity of this process adversely (Olszewski *et al.*, 2014; Sitko *et al.*, 2019).

Compared to other ions, the concentration of phosphates in the soil solution is very low (Mollier and Pellerin, 1999), and low temperatures after plant emergence additionally inhibit the uptake of phosphorus (Mozafar, Schreiber and Oertli, 1993). An adequate concentration of P in plant tissues helps to maintain high intensity of photosynthesis which enhances the production of aerial biomass (Hawkesford *et al.*, 2012).

Magnesium is easily leached, especially from acidic soils, and the uptake of Mg^{2+} by plant roots can be hindered due to competition with other ions. A deficit of this element is becoming an increasingly serious factor limiting plant production (Gaj *et al.*, 2018). The uptake of nutrients and effectiveness of applied NPK fertilisers are depressed considerably when sulphur is deficient (Tirupathi *et al.*, 2016). The application of Mg and S improves maize yield and agronomic efficiency of fertilisation compared to the use of NPK alone (Garba *et al.*, 2020).

Concentrations of nutrients and yield of grain and straw can be used to determine the removal of nutrients from soil, which can be the basis for determining the necessary doses of fertiliser (Heckman *et al.*, 2003). In turn, the content of nutrients in straw and straw yield provide information about the amounts of nutrients returned to soil when the straw is ploughed into the soil (Moschler *et al.*, 1972). As regards some nutrients whose cycling is associated with the organic fraction (N, P and S), their concentrations relative to the C-org. content in post-harvest residues determine the rates and relationships between immobilisation and mineralisation processes (Zibilske and Materon, 2005).

The objective of this work has been to determine the influence of fertilisation with urea-ammonium nitrate supplemented with P, Mg or S on the content and uptake of macronutrients in grain and straw of maize.

Table 1. Design of the fertilisation

Number of object	Date of application	
	prior sowing (100 kg N·ha^{-1})	4-6 leaf phase (14–16 BBCH) (80 kg N·ha^{-1})
I[1)]	control, no nitrogen fertilisation	
II[1)]	ammonium nitrate	urea
III[1)]	UAN	urea
IV[1)]	UAN	UAN
V[1)]	UAN + S	UAN + Mg
VI[2)]	UAN + P(Medium)	UAN + P(Medium)
VII[3)]	UAN + P(Starter)	UAN + S
VIII[3)]	UAN + P(Starter)	UAN + Mg

[1)] Pre-sowing dose of phosphorus (37.36 kg P·ha^{-1}) in the form of granulated fertiliser.
[2)] Pre-sowing dose of phosphorus (4.18 kg P·ha^{-1}) in the form of granulated fertiliser.
[3)] Pre-sowing fertilisation with phosphorus in a liquid form.
Explanations: The BBCH-scale is used to identify the phenological development stages of plants. BBCH-scales have been developed for a range of crop species where similar growth stages of each plant are given the same code. The abbreviation BBCH derives from the names of the originally participating stakeholders: "Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie".
Source: own elaboration.

MATERIALS AND METHODS

DESCRIPTION OF THE EXPERIMENT

The experiment was conducted in 2015–2017. It was set up on production fields owned by the Production and Experimental Enterprise located in Bałcyny (Pol. Zakład Produkcyjono-Doświadczalny Sp. z o.o. w Bałcynach) (51.6667 N, 18.1667 E). The surface area of a plot for harvest was 450 m^2. In each year, the experiment was set up on lessivé soil formed from medium clay (IUSS Working Group WRB, 2015). Prior to the experiment, the soil was slightly acidic in reaction (pH (1 mol KCl·dm^{-3}) = 5.70–6.33) and contained C-org. – 12.50–13.20 g·kg^{-1}. The content of available forms of macronutrients was as follows: P – 97.8–135.5, K – 182.7–224.1, Mg – 52.0–82.2, S–SO_4^{2-} – 4.0–14.0 mg·kg^{-1}. The soil available nutrient levels were measured as follows: P – PN-R-04023:1996, K – PN-R-04022:1996+Az1:2002, Mg – PN-R-04020:1994+Az1:2004 and pH – PN-ISO 10390:1997. Total organic carbon was measured with a Vario Max Cube CN Elementar analyser. The content of S–SO_4 in soil was determined by the nephelometric method.

The single-factor field experiments with eight fertilisation objects were laid out in a random-block design with 4 replicates. The following nitrogen fertilisers were applied in the experiment: ammonium nitrate, urea, UAN – 32%N; UAN + S – 26% N + 3% S; UAN + P(Medium) – 26% N and 4.80% P; UAN + P(Starter) – 21% N and 7.86% P; UAN + Mg – 20% N + 4% Mg (Tab. 1).

The maize cultivar 'NK Borago' (a single hybrid) with large, flex cobs, well filled with glassy flint kernels, was sown. It is an early variety (FAO 220) with excellent vernal vigour (Agrocentrum, 2013).

In 2015 and 2016, maize was seeded in the last ten days of April, while in 2017 it was sown on 1 May, each time in the amount of 90,000 germinating kernels per 1 ha, in rows set 75 cm apart. In objects II–VIII, nitrogen fertilisation was applied in the quantity of 180 kg N·ha^{-1}, split into two doses: 100 kg N·ha^{-1} before sowing and 80 kg N·ha^{-1} at the phase of 4–6 leaf, in the forms defined in the design of the experiment. Before sowing, soil in objects I–V was enriched with 37.36 kg P·ha^{-1} (as triple superphosphate). Soil in object VI, before sowing maize, was enriched with 4.18 kg P·ha^{-1} in the solid form and 16.58 kg P·ha^{-1} as UAN + P(Medium), while the remaining dose (16.58 kg P·ha^{-1}) was applied as top-dressing fertilisation mainly in the form of UAN + P(Medium). In objects VII and VIII, the entire dose of phosphorus (37.36 kg P·ha^{-1}) was applied in the liquid form (UAN + P(Starter)). All the objects were supplied 160.02 kg K·ha^{-1} as 60% potassium salt before sowing the maize. At the 16–18 BBCH maize development phase, Insol Zn in a dose of 2 dm^3·ha^{-1} (100 g Zn·ha^{-1}) was applied to maize leaves. The regulation of weed infestation was performed at the stage 3 of the true leaf (BBCH 13) using Lumax 537.5 SE at the dose of 3.5 dm^3·ha^{-1}. Maize harvest took place in the last ten days of October in the first and second year of the experiment, being delayed in the last year due to heavy rainfalls until the second ten days of November.

CHEMICAL ANALYSIS METHODS

During maize harvest, grain and straw samples were taken from each plot for chemical analyses. In the laboratory, the plant material was dried in the temperature of 60°C in a dryer with forced air circulation. Then, the plant material was ground in a laboratory grinder. The content of chemical elements is expressed in dry matter (drying temperature 105°C).

The content of macronutrients in grain and straw (P, K, Ca, Mg) was determined in plant material previously digested in concentrated sulphuric acid (H_2SO_4) with added hydrogen dioxide

(H_2O_2) as an oxidant (Büchi Speed Digester K-439). The mineralised plant material was submitted to the determinations of: P by colorimetry with the vanadium-molybdenum method (Shmandzu UV 1201V), K and Ca with the atomic emission spectrometry (AES) method on a Jenway LTD PEP 7 apparatus, and Mg with the atomic absorption spectrometry (AAS) method on a Shimandzu AA-6800 apparatus. The content of S was determined by nephelometry (Ostrowska, Gawliński and Szczubiałka, 1991) having first mineralised the plant material in a mixture of chlorine and nitric acids ($HClO_4$ and HNO_3 in a 1:1 ratio) with added magnesium nitrate(V) ($Mg(NO_3)_2$) (Khan, 2012).

METEOROLOGICAL CONDITIONS

In the 1st and 3rd year of the experiment (Tab. 2), the emergence of maize plants proceeded during a period of relatively modest rainfalls (Selyaninov hydrothermal coefficient K = 0.68 and 0.84, respectively) (Bac, Koźmiński and Rojek, 1998). The best conditions for plant emergence were noted in the second year of the study. During the 2nd and 3rd research year, the weather conditions in June, that is the time when maize plants go through vegetative development, ensured adequate moisture and the air temperature was close to the long-term average. However, during the 1st year, the atmospheric precipitations were much below the long-term mean.

Table 2. Characteristics of the meteorological conditions during the experiment

Year of study	Selyaninov hydrothermal coefficient (K) for						
	April	May	June	July	Aug	Sept	Oct
2015	1.08	0.68	0.91	1.27	0.19	1.19	1.01
2016	1.26	1.53	1.23	2.41	1.32	0.39	4.51
2017	2.59	0.84	2.19	1.98	0.95	5.21	5.52

Explanations: K = 0–0.5 – drought, 0.6–1.0 – dry weather, 1.1–2.0 – wet weather, >2.1 – very wet weather.
Source: own elaboration.

In the 1st year of the experiment, July was also characterised by the lowest value of the Selyaninov hydrothermal coefficient (K = 1.27) compared to the two subsequent years, when it reached 2.41 and 1.98, respectively. The end of maize flowering and beginning of the milk maturity stage occurred in August. During the 1st year, this month was marked by a drought (K = 0.19), which was due to high air temperatures and low rainfall. During the 2nd and 3rd year of the experiment, this coefficient in August reached 1.32 (humid) and 0.95 (dry weather).

In September, the mean daily temperature in 2015–2017 was approximately the same as the long-term one. In the 1st year of the study, the total atmospheric rainfall in September did not diverge from the average for 1981–2010, whereas the 2nd year was dry (K = 0.39). September and October 2017 noted the record high rainfalls (K = 5.21 and 5.52, respectively).

The results underwent statistical processing by applying analysis of variance (ANOVA) in a Statistica 13.3® software package. The analysis of variance was performed as a 3-year series for one-way design. Differences between the means were compared with the Tukey's post-hoc tests at significance $p < 0.05$.

RESULTS AND DISCUSSION

The significantly lowest content of P (3.18 g·kg^{-1} DM) was determined in maize grown on the control plots in the first year of the experiment (Tab. 3). The significantly highest concentration of this element (5.16 g·kg^{-1} DM) was found in maize from the (UAN + P(Starter))/(UAN + Mg) treatment. The content of P in maize grain in the three research years was significantly varied. The highest content of this element (4.77 g·kg^{-1} DM) accumulated in maize grain in the 2nd year of the experiment, while the smallest quantity (less by 28.30%) was determined in the 1st year. Nitrogen fertilisation increased the content of P considerably, although only the grain of maize fertilised with (UAN + P(Starter))/(UAN + Mg) contained significantly more P (4.25 g·kg^{-1} DM) than maize grain from the control treatment (3.65 g·kg^{-1} DM).

The least P (1.57 g·kg^{-1} DM) was found in the straw of maize cultivated on the control plots and on plots fertilised with UAN/urea in the third year of the experiment (Tab. 4). The significantly highest content of P (3.32 g·kg^{-1} DM) was obtained in the 2nd year of the experiment, in the straw of maize fertilised with (UAN + S)/(UAN + Mg). No significant differences were observed with respect to average P content in maize straw depending on the fertilisation variants.

The content of P in maize straw and grain determined in this study was higher than reported by others. The P content in maize grain given by Polish researchers, depending on the type of soil on which their experiments had been set up, soil tillage, applied fertilisation and the maize cultivar, range from 1.52 to 3.42 g·kg^{-1} (Szulc *et al.*, 2007; Baran *et al.*, 2011; Gąsiorowska, Makarewicz and Nowosielska, 2011; Meller and Bilenda, 2013). According to Stępień, Wojtkowiak and Kolankowska (2021), the content, of P in maize grain changed depending on the year of their experiment. This effect was also observed in our study. Pawłowski, Augustyniak and Barczak (2018) suggested that sulphur fertilisation caused a significant decrease in the P content of maize grain. Same as in maize grain, the content of P in maize straw determined in our study was higher than the content reported in Polish references (0.57–1.35 g·kg^{-1}) (Szulc *et al.*, 2007; Baran *et al.*, 2011). According to Ferreira *et al.* (2014), the plant breeding efforts have led to decreased P and K levels in vegetative organs of maize, which may be linked to the less efficient redistribution of these elements to grain.

The significantly least K was contained in the grain of maize fertilised before sowing and then by top-dressing with UAN and with (UAN + P(Starter))/(UAN + Mg) – 3.22 and 3.18 g·kg^{-1} DM, respectively in the third year of the experiment (Tab. 3). The significantly highest amount of K (5.99 g·kg^{-1} DM) accumulated in maize grain harvested from the UAN/urea fertilised object in the 1st year of the experiment. The K content was significantly varied in the three years of the study. Most of this element (5.41 g·kg^{-1} DM) was determined in 2015 year, decreasing by over 36% in 2017. However, in view of the varied weather conditions during the experiment and considering the treatment-related mean results, it turned out that the fertilisation variants did not have a significant effect on the K content in maize grain.

The significantly highest K content was determined in the straw of maize harvested from the (UAN + P(Starter))/(UAN + Mg) and UAN/urea plots in the third year of the experiment (Tab. 4). In turn, the least K (13.89 g·kg^{-1} DM) was found in the

Table 3. Content of macronutrients in common maize grain (mean ±standard deviation in g·kg^{-1} DM)

Number of object	P			K			Ca			Mg			S		
	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
I	3.18^{a} ±0.02	4.34^{g} ±0.03	3.45^{c} ±0.02	5.44^{i} ±0.18	4.97^{de} ±0.03	3.44^{b} ±0.00	0.88^{ijk} ±0.04	0.89^{jk} ±0.02	0.60^{d} ±0.00	$1.94^{f\text{-}I}$ ±0.03	1.84^{d} ±0.02	1.04^{a} ±0.01	1.51^{fg} ±0.02	1.20^{b} ±0.02	1.41^{de} ±0.01
II	3.32^{b} ±0.06	4.73^{i} ±0.06	3.95^{e} ±0.10	5.20^{fgh} ±0.10	4.93^{d} ±0.00	3.41^{b} ±0.00	0.86^{ij} ±0.01	$0.83^{e\text{-}h}$ ±0.01	0.48^{b} ±0.00	1.97^{hi} ±0.08	1.86^{de} ±0.04	1.06^{a} ±0.02	1.11^{a} ±0.05	1.52^{fgh} ±0.05	1.49^{fg} ±0.03
III	3.38^{bc} ±0.04	4.89^{jk} ±0.02	4.13^{f} ±0.03	5.99^{k} ±0.03	4.92^{d} ±0.03	3.79^{c} ±0.01	0.85^{hi} ±0.02	0.80^{e} ±0.01	0.51^{c} ±0.00	1.92^{fg} ±0.03	1.94^{fgh} ±0.01	1.06^{a} ±0.02	1.07^{a} ±0.03	1.37^{d} ±0.03	1.36^{d} ±0.00
IV	3.36^{bc} ±0.01	4.51^{h} ±0.03	3.42^{c} ±0.05	5.21^{gh} ±0.14	5.04^{de} ±0.11	3.22^{a} ±0.03	0.87^{ij} ±0.03	0.83^{fgh} ±0.02	0.46^{b} ±0.01	1.93^{fgh} ±0.04	1.93^{fgh} ±0.01	1.03^{a} ±0.00	1.49^{fg} ±0.01	1.53^{gh} ±0.03	1.58^{h} ±0.03
V	3.41^{c} ±0.12	4.84^{j} ±0.11	3.97^{e} ±0.03	5.21^{gh} ±0.01	5.08^{ef} ±0.02	3.40^{b} ±0.01	0.87^{ij} ±0.01	0.87^{ij} ±0.02	0.41^{a} ±0.00	1.90^{ef} ±0.01	1.98^{i} ±0.05	1.02^{a} ±0.01	1.65^{i} ±0.07	1.50^{fg} ±0.03	1.54^{gh} ±0.02
VI	3.58^{d} ±0.04	4.70^{i} ±0.08	3.99^{e} ±0.03	5.29^{h} ±0.04	4.97^{de} ±0.08	3.36^{b} ±0.08	0.82^{efg} ±0.02	0.90^{k} ±0.03	0.47^{b} ±0.00	1.93^{fgh} ±0.01	1.96^{ghi} ±0.01	1.02^{a} ±0.02	1.68^{ij} ±0.07	1.48^{fg} ±0.07	1.70^{ijk} ±0.03
VII	3.54^{d} ±0.08	4.97^{k} ±0.01	4.00^{e} ±0.04	5.09^{efg} ±0.02	5.49^{i} ±0.19	3.77^{c} ±0.02	0.80^{ef} ±0.00	0.83^{gh} ±0.03	0.54^{c} ±0.00	1.90^{ef} ±0.02	$1.94^{f\text{-}I}$ ±0.04	1.11^{b} ±0.01	1.73^{jk} ±0.02	1.41^{de} ±0.04	1.74^{k} ±0.04
VIII	3.58^{d} ±0.08	5.16^{l} ±0.01	4.01^{e} ±0.07	5.86^{j} ±0.00	4.95^{d} ±0.03	3.18^{a} ±0.03	0.80^{ef} ±0.03	0.86^{hij} ±0.02	0.47^{b} ±0.00	1.97^{ghi} ±0.01	1.99^{i} ±0.04	1.17^{b} ±0.02	1.46^{ef} ±0.01	1.40^{d} ±0.03	1.30c ±0.01
Average	3.42^{A} ±0.14	4.77^{C} ±0.25	3.86^{B} ±0.26	5.41^{C} ±0.89	5.04^{B} ±0.33	3.45^{A} ±0.01	0.84^{A} ±0.04	0.85^{A} ±0.04	0.49^{B} ±0.05	1.93^{A} ±0.04	1.93^{A} ±0.06	1.06^{B} ±0.05	1.46^{A} ±0.24	1.43^{A} ±0.11	1.51^{A} ±0.15
Average for fertilisation															
I	3.65^{A} ±0.53			4.62^{A} ±0.91			0.79^{A} ±0.14			1.61^{A} ±0.43			1.37^{A} ±0.14		
II	4.00^{AB} ±0.61			4.51^{A} ±0.84			0.72^{A} ±0.19			1.63^{A} ±0.43			1.37^{A} ±0.20		
III	4.13^{AB} ±0.66			4.90^{A} ±0.95			0.72^{A} ±0.16			1.64^{A} ±0.43			1.27^{A} ±0.15		
IV	3.76^{AB} ±0.56			4.49^{A} ±0.96			0.72^{A} ±0.19			1.63^{A} ±0.45			1.53^{B} ±0.04		
V	4.07^{AB} ±0.63			4.56^{A} ±0.88			0.72^{A} ±0.23			1.63^{A} ±0.46			1.56^{B} ±0.08		
VI	4.09^{AB} 0.49			4.54^{A} ±0.89			0.73^{A} ±0.20			1.64^{A} ±0.46			1.62^{B} ±0.11		
VII	4.17^{AB} ±0.63			4.78^{A} ± 0.79			0.72^{A} ±0.14			1.65^{A} ±0.40			1.63^{B} ±0.16		
VIII	4.25^{B} ±0.71			4.66^{A} ±1.18			0.71^{A} ±0.18			1.71^{A} ±0.40			1.39^{A} ±0.07		

Explanations: number of object see Table 1, data marked with different letters differ significantly at $p < 0.05$.
Source: own study.

Table 4. Content of macronutrients in common maize straw (mean ±standard deviation in g·kg^{-1} DM)

Number of object	P			K			Ca			Mg			S		
	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
I	1.73^{cd} ±0.05	2.45^{k} ±0.08	1.57^{a} ±0.08	16.49^{b} ±0.07	13.89^{a} ±0.33	18.50^{ef} ±0.12	4.54^{g} ±0.26	3.95^{c} ±0.02	3.33^{a} ±0.11	2.10^{kl} ±0.12	0.84^{b} ±0.04	1.95^{hij} ±0.04	1.54^{g} ±0.03	1.03^{c} ±0.02	1.22^{de} ±0.01
II	1.95^{hi} ±0.03	2.70^{l} ±0.08	1.65^{b} ±0.02	20.86^{j} ±0.11	19.57^{hi} ±0.00	19.66^{hi} ±0.39	5.27^{j} ±0.06	4.31^{ef} ±0.04	4.24^{de} ±0.11	2.17^{lm} ±0.10	0.89^{bc} ±0.03	1.77^{f} ±0.10	1.60^{gh} ±0.04	0.91^{a} ±0.03	1.29^{ef} ±0.04
III	1.67^{b} $±0.03^{c}$	2.70^{l} ±0.02	1.57^{a} ±0.02	17.17^{c} ±0.14	18.04^{d} ±0.28	25.15^{m} ±0.04	5.21^{j} ±0.04	4.56^{g} ±0.04	3.78^{b} ±0.05	2.32^{n} ±0.02	1.02^{de} ±0.06	1.82^{f} ±0.02	1.60^{gh} ±0.05	0.88^{a} ±0.03	1.27^{ef} ±0.10
IV	1.88^{fgh} ±0.06	2.64^{l} ±0.10	1.77^{de} ±0.02	18.89^{fg} ±0.13	19.29^{gh} ±0.03	23.44^{l} ±0.05	4.49^{j} ±0.05	4.14^{d} ±0.00	4.24^{de} ±0.07	2.30^{n} ±0.05	0.89^{bc} ±0.03	1.82^{fg} ±0.08	1.60^{gh} ±0.01	0.98^{bc} ±0.00	1.19^{d} ±0.04
V	1.80^{def} ±0.04	3.32^{o} ±0.02	2.05^{j} ±0.00	17.27^{c} ±0.06	18.83^{f} ±0.09	22.94^{k} ±0.48	4.73^{h} ±0.01	4.98^{i} ±0.02	4.14^{d} ±0.10	2.17^{lm} ±0.03	1.08^{e} ±0.03	1.96^{hij} ±0.02	1.62^{h} ±0.01	0.91^{ab} ±0.02	1.24^{def} ±0.09
VI	1.89^{gh} ±0.07	3.21^{n} ±0.05	2.00^{ij} ±0.00	19.81^{i} ±0.06	18.47^{ef} ±0.01	19.90^{i} ±0.08	4.97^{i} ±0.02	4.46^{fg} ±0.04	4.74^{h} ±0.07	2.02^{ijk} ±0.13	0.88^{b} ±0.02	1.92^{gh} ±0.07	1.63^{h} ±0.02	1.01^{c} ±0.00	1.31^{f} ±0.06
VII	1.86^{fg} ±0.06	2.89^{m} ±0.03	2.00^{ij} ±0.06	17.25^{c} ±0.22	21.13^{j} ±0.66	23.64^{l} ±0.41	5.26^{j} ±0.08	5.20^{j} ±0.18	4.20^{de} ±0.06	2.20^{lm} ±0.00	0.97^{cd} ±0.01	1.94^{hi} ±0.03	1.54^{g} ±0.03	1.05^{c} ±0.03	1.30^{f} ±0.05
VIII	1.82^{efg} ±0.02	2.85^{m} ±0.02	1.84^{efg} ±0.05	19.54^{hi} ±0.17	18.36^{de} ±0.36	25.47^{m} ±0.41	5.30^{j} ±0.20	4.90^{i} ±0.09	4.48^{g} ±0.04	2.23^{mn} ±0.06	0.71^{a} ±0.02	2.04^{jk} ±0.03	1.66^{h} ±0.06	1.04^{c} ±0.06	1.28^{ef} ±0.03
Average	1.83^{A} ±0.10	2.84^{B} ±0.028	1.81^{A} ±0.19	18.41^{A} ±1.51	18.45^{A} ±2.00	22.34^{B} ±2.56	4.97^{C} ±0.34	4.56^{B} ±0.42	4.14^{A} ±0.42	2.19^{C} ±0.12	0.91^{A} ±0.11	1.90^{B} ±0.10	1.60^{C} ±0.05	0.98^{A} ±0.07	1.26^{B} ±0.06
Average for fertilisation															
I	1.91^{A} ±0.41			16.29^{B} ±2.01			3.94^{C} ±0.54			1.63^{A} ±0.60			1.26^{A} ±0.22		
II	2.10^{A} ±0.47			20.03^{A} ±0.66			4.61^{AB} ±0.50			1.61^{A} ±0.57			1.27^{A} ±0.30		
III	1.98^{A} ±0.54			20.12^{A}±3.79			4.52^{AB} ±0.62			1.72^{A} ±0.57			1.25^{A} ±0.32		
IV	2.09^{A} ±0.41			20.54^{A} ±2.18			4.29^{BC} ±0.16			1.67^{A} ±0.62			1.26^{A} ±0.27		
V	2.39^{A} ±0.70			19.68^{A}±2.55			4.62^{AB} ±0.37			1.73^{A} ±0.50			1.26^{A} ±0.31		
VI	2.37^{A} ±0.63			19.39^{A} ±0.70			4.72^{A} ±0.23			1.60^{A} ±0.55			1.32^{A} ±0.27		
VII	2.25^{A} ±0.49			20.68^{A} ±2.82			4.89^{A} ±0.52			1.70^{A} ±0.56			1.30^{A} ±0.22		
VIII	2.17^{A} ±0.51			21.12^{A} ±3.31			4.89^{A} ±0.37			1.66^{A} ±0.72			1.33^{A} ±0.28		

Explanations as in Tab. 3.
Source: own study.

straw of maize grown on the control plots in the 2nd year of the study. The significantly highest K content (22.34 g·kg^{-1} DM) was determined in the maize straw obtained in the 3rd year of the experiment, when it was about 21% higher than in the previous years. Relative to the control, fertilisation significantly raised the K content of maize straw: from 19.03% (UAN + P(Medium))/(UAN + P(Medium)) to 29.65% (UAN + P(Starter)/(UAN + Mg).

A thorough perusal of the relevant references indicates that the content of K in maize grain can vary over a wide range of values. The concentration of this element in grain depended on the type of soil, applied fertilisation (Pawłowski, Augustyniak and Barczak, 2018), and on the weather conditions and date of sowing (Gąsiorowska, Makarewicz and Nowosielska, 2011). A delayed sowing date significantly decreased the content of K in grain. Furthermore, the content of K in maize grain determined by Szulc *et al.* (2007) ranged from 3.50 to 3.76 g·kg^{-1} and tended to be higher under the effect of phosphorus. Slightly higher concentrations of K in maize grains were reported by Stępień, Wojtkowiak and Kolankowska (2021) – depending on the year of the experiment, maize grain contained from 4.03 to 4.58 g·kg^{-1}. Even more K in maize grain (6.69–7.45 g K·kg^{-1}) was determined by Meller and Bilenda (2013).

In this study, the straw content of K was much higher than given in the relevant literature. For example, Szulc *et al.* (2007) or Baran *et al.* (2011) determined that the K concentrations in straw ranged from 8.26 to 13.69 g·kg^{-1} and depended on a maize cultivar grown as well as a dose of phosphorus fertilisers and a way of their application. According to Nenova *et al.* (2019), concentrations of P and K in grain and in the vegetative parts of maize differed significantly between the years of the study. Most P and K accumulated in the vegetative biomass of maize grown without fertilisation. Çelik *et al.* (2010) noted that higher K doses resulted in decreased concentrations of P, Mg and Ca in maize leaves and roots. Low temperature in the early growth stages of maize can lead to the depressed plant content of P and K (Cholakova-Bimbalova and Vasilev, 2015).

The highest Ca content (0.90 g·kg^{-1} DM) was determined in the 2nd year of the experiment, in the grain of maize fertilised before sowing and by top-dressing with UAN + P(Medium), whereas the least of this element (0.41 g·kg^{-1} DM) accumulated in grain obtained from the fertilisation variant (UAN + S)/(UAN + Mg) in the 3rd year of the study (Tab. 3). Same as K concentrations, significantly the smallest amount of Ca was determined in the grain of maize harvested in the third year (less by approximately 41% than in the previous years). The fertilisation applied had no significant effect on the Ca content in grain.

The lowest Ca content (3.33 g·kg^{-1} DM) was determined in the 3rd year of the trials, in the straw of maize from the control treatment (Tab. 4). The highest Ca was contained in the maize straw harvested in the 1st year from the plots fertilised with (UAN + P(Starter))/(UAN + Mg), (UAN + P(Starter))/(UAN + S) and with ammonium nitrate/urea (5.30, 5.26 and 5.27 g Ca·kg^{-1} DM, respectively). The weather conditions significantly affected the content of Ca in straw. The least of this element accumulated in the straw of maize grown in the 3rd year (4.14 g Ca·kg^{-1} DM), whereas its more effective accumulation took place in the first year (4.97 g Ca·kg^{-1} DM). In comparison with the control, fertilisation significantly increased the Ca content, and its highest amount was found in the straw of maize fertilised before sowing with UAN + P(Starter), and then, by top-dressing, with UAN + Mg or UAN + S (4.89 g Ca·kg^{-1} DM).

The literature also provides evidence for a wide range of Ca concentrations in maize. For example, Pawłowski, Augustyniak and Barczak (2018) showed that grain of maize cultivated on chernozem soils (0.20 g·kg^{-1}) than on podsols or luvisols (0.08 g·kg^{-1}). The mentioned authors proved that sulphur fertilisation caused a significant increase in the grain Ca content. Similarly small amounts of Ca (0.07–0.09 g·kg^{-1}) in maize grain were determined by Szulc *et al.* (2007). In turn, Meller and Bilenda (2013) determined the Ca content in maize grain to be between 0.32 and 0.44 g·kg^{-1}, depending on fertilisation. Stępień, Wojtkowiak and Kolankowska (2021) found even higher concentrations of Ca in maize grain (from 0.55 to 0.66 g Ca·kg^{-1}). Furthermore, Gąsiorowska, Makarewicz and Nowosielska (2011) showed the significant impact of the weather factors and sowing date on the content of this element. At later dates of sowing, the content of Ca in maize grain was lower. The maize grain analysed by Baran *et al.* (2011) contained as much as 1.14 g Ca·kg^{-1}, while the straw content of Ca equalled 3.30 g·kg^{-1}. In turn, Szulc *et al.* (2007) determined between 4.45 and 5.45g Ca·kg^{-1} in maize straw.

In our study, the significantly highest Mg content in maize grain was found in the 2nd year of the experiment following the fertilisation treatments with (UAN + P(Starter))/(UAN + Mg) and (UAN + S)/(UAN + Mg) – 1.99 and 1.98 g Mg·kg^{-1} DM, respectively (Tab. 3). Maize grain in the 1st and 2nd year of the study contained on average 1.93 g Mg·kg^{-1} DM, while in the 3rd year it was lower by as much as 45%. The fertilisation applied in our study did not have a significant influence on the concentration of Mg in grain.

The highest Mg content (2.30–2.32 g·kg^{-1} DM) was determined in the straw of maize fertilised with UAN pre-sowing and with UAN or urea by top-dressing in the first year of the experiment (Tab. 4). The lowest Mg content (0.71 g·kg^{-1} DM) appeared in the 2nd year, in the straw of maize from the treatment (UAN + P(Starter))/(UAN + Mg). The maize straw harvested in the 1st year contained significantly most Mg (2.19 g·kg^{-1} DM), while being 2.4-fold lower in the 2nd year of the experiment. The fertilisation applied in our study did not have a significant effect on the Mg content in maize straw.

The data on the Mg content in maize grain given in the available references are similar to our results. For example, Szulc *et al.* (2007) reported the Mg content in maize grain to vary from 0.93 to 1.04 g·kg^{-1}, while Baran *et al.* (2011) determined the average Mg content in maize grain to be approximately 1.14 g·kg^{-1}. Stępień, Wojtkowiak and Kolankowska (2021), depending on the year of their research, determined between 1.05 and 1.38 g Mg·kg^{-1} in maize grain. In another experiment, the Mg content in grain (1.08–1.29 g·kg^{-1}) depended on the weather conditions, and was increased by postponing the date of sowing (Gąsiorowska, Makarewicz and Nowosielska, 2011). Baran *et al.* (2011) determined that the Mg content in maize straw was 1.91 g·kg^{-1}, which is slightly more than reported by Szulc *et al.* (2007) – from 1.48 to 1.59 g·kg^{-1} DM.

The content of S in maize grain varied from 1.07 to 1.74 g·kg^{-1} DM (Tab. 3). Most of this element was determined in the grain harvested in the 3rd year of the experiment from the plots fertilised with (UAN + P(Starter))/(UAN+S), while the lowest S content was found in the grain of maize fertilised with UAN/urea in the first year of the study. Differences in the

S content in grain between the three years of the experiment were insignificant. Nitrogen fertilisation only slightly modified the content of S in maize grain. Most of this element accumulated in the grain of maize fertilised with (UAN + P(Starter))/(UAN + S) and with UAN + P(Medium) before sowing and by top-dressing. The content of S in straw was from 0.88 to 1.66 g·kg^{-1} DM (Tab. 4). The highest concentration of this element was found in the first year of the experiment in the straw from maize fertilised with UAN + P(Starter))/(UAN + Mg), whereas the highest S content was determined in the 2nd year in the straw from maize supplied UAN/urea. Most S (1.60 g·kg^{-1} DM) was accumulated in straw in the first year of the study. In the subsequent years, the content of S in straw was significantly lower, by 38.37% in the 2nd and by 21.25% less in the 3rd year of the experiment. Different fertilisation variants tested did not have a significant effect on S in maize straw.

The results of our study point to a much higher S content than the data given in the relevant references. According to Barczak, Murawska and Spychaj-Fabisiak (2011), the grain of maize contained from 0.85 to 1.13 g S·kg^{-1}. Sulphur fertilisation raised the concentration of this element in maize grain. In a study by Filipek-Mazur, Lepiarczyk and Tabak (2013), the content of sulphur in maize grain ranged from 0.72 to 0.94 g·kg^{-1}. The highest S content was in the grain of maize fertilised with nitrogen and sulphur in a 2:1 ratio. Iżewska and Wołoszyk (2015) reported that the content of S in the straw of maize fertilised with NPK was 0.81 g S·kg^{-1}, but when NK fertilisation was supplemented with sewage slush ash, the concentration of S rose to 1.06 g S·kg^{-1} of straw.

The removal of nutrients with crop yields is a product of the yield and concentrations of these nutrients in the main yield and by-products. Maize absorbed the significantly highest amount of P (about 100 kg·ha^{-1}) in the 2nd year of the experiment, while in the first year its accumulation was 3-fold lower (Fig. 1). The highest removal of K (about 350 kg·ha^{-1}) was also noted in the second year, being the lowest one was in the first year (about 150 kg·ha^{-1}). The average Ca removal in the 2nd year was about 80 kg·ha^{-1}, compared to around 40 kg·ha^{-1} in the other two years. The removal of Mg ranged from about 25 kg·ha^{-1} (3rd year) to 35 kg·ha^{-1} (2nd year). The uptake of S with the aerial mass yield of maize varied from 20 kg·ha^{-1} (1st year) to ~31 kg·ha^{-1} in the 2nd year of the experiment.

The smallest P removal (~45 kg·ha^{-1}) appeared in the case of maize from the control plots (Fig. 2). Maize fertilised with nitrogen took up 60–66 kg P·ha^{-1} (differences were not significant). The significantly lowest K uptake (~170 kg·ha^{-1}) was demonstrated by maize grown without nitrogen fertilisation (control). In contrast, the highest K removal (252–262 kg·ha^{-1}) occurred after maize was fertilised with UAN/UAN or with UAN/(UAN + P(Starter)) prior to sowing and with UAN + Mg or UAN + S as top-dressing applications (objects IV, VII, VIII). The uptake of Ca by the maize aerial mass ranged from 41 (control) to

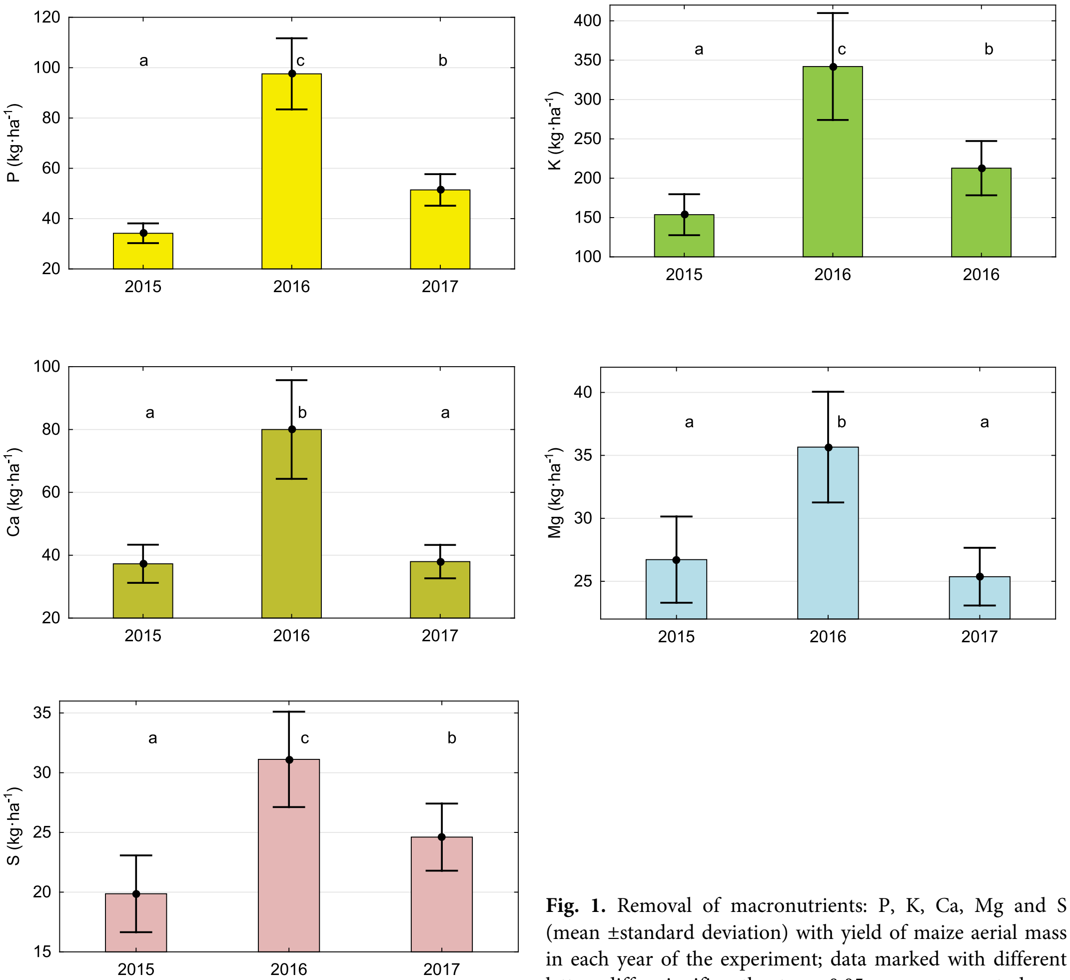

Fig. 1. Removal of macronutrients: P, K, Ca, Mg and S (mean ±standard deviation) with yield of maize aerial mass in each year of the experiment; data marked with different letters differ significantly at p < 0.05; source: own study

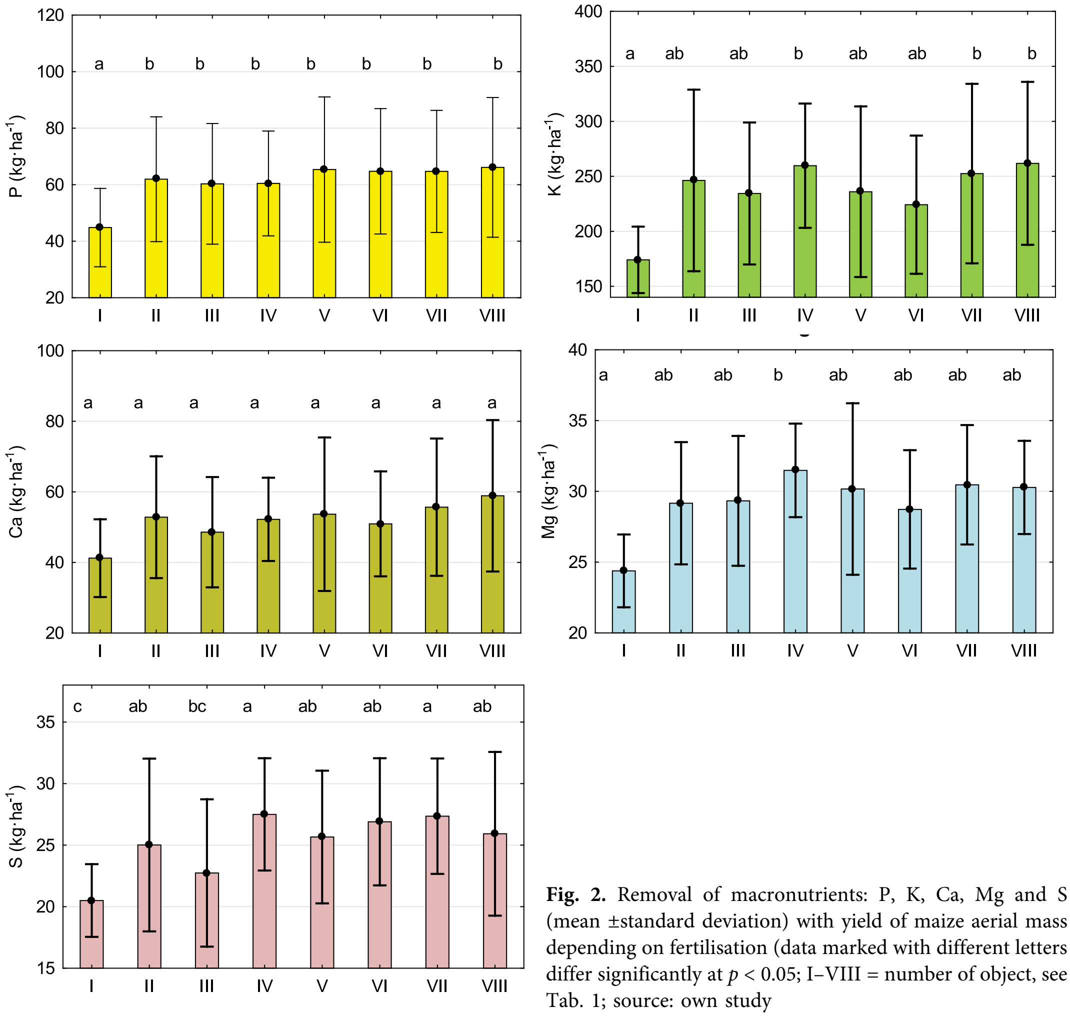

Fig. 2. Removal of macronutrients: P, K, Ca, Mg and S (mean ±standard deviation) with yield of maize aerial mass depending on fertilisation (data marked with different letters differ significantly at $p < 0.05$; I–VIII = number of object, see Tab. 1; source: own study

59 kg·ha^{-1} (UAN + P(Starter))/(UAN + Mg). Same as the P removal, the applied fertilisation did not have a significant effect on the removal of Ca. The significantly smallest Mg removal (~24 kg·ha^{-1}) was observed on the control plots. The tested fertilisation significantly increased the Mg uptake, but it was only the maize fertilised before sowing and by top-dressing with UAN that took up significantly more of this element (~31 kg·ha^{-1}) than the control plants. Significantly the least of S was taken up by maize from the control treatment (~20 kg·ha^{-1}), while significantly more S (~27 kg·ha^{-1}) was absorbed by maize fertilised by UAN/UAN and (UAN + P(Starter))/(UAN + S) (objects IV and VII).

The uptake of NPK from applied fertilisers, according to Pepó and Karancsi (2017), depends on the genotype of a maize cultivar and the weather conditions during its cultivation. Skowrońska and Filipek (2010) maintained that fertilisation did not have an effect on the uptake of nutrients by maize grown in soil rich in available nutrients.

In our study, the accumulation of P in maize aerial biomass was in general higher than the amounts reported by other authors. According to Piszcz (2002), maize took up between 17.4 and 36.1 kg P·ha^{-1} in its final yield. The N fertilisation level did not have an effect on the uptake of P by the aerial biomass of maize (Wrońska *et al.*, 2007). On the other hand, fertilisation with zinc stimulated the accumulation of P in the aerial mass of maize. The uptake of P by maize depended on the genotype of a cultivar as well as the type of phosphorus fertilisers and their application technology (Baran *et al.*, 2011). The study conducted by Ray *et al.* (2019) showed that the removal of P with maize grain ranged from 14.60 to 42.78 kg P·ha^{-1} and from 21.40 to 48.90 kg K·ha^{-1}. The accumulation of these elements in grain depended on the weather conditions in every plant growing season, the cultivar grown and the level of NPK fertilisation. The total P uptake depended on the cultivar and fertilisation, while that of K was affected only by fertilisation (Ray *et al.*, 2020). Meller and Bilenda (2013) found that the uptake of P by maize was even higher than determined in our study, and ranged from 89.6 to 103.5 kg·ha^{-1}.

Some authors maintain that fertilisation had an effect on the K removal with aerial biomass of maize, in which they agree with our findings. According to Wieremiej (2016), maize grown without fertilisation took up 47.47 kg K·ha^{-1}, and when fertilised with NPK, it removed 175.1 kg K·ha^{-1}. In the study conducted by Meller and Bilenda (2013), the uptake of K by maize ranged from 378.9 to 596.4 kg·ha^{-1}. Depending on a maize cultivar, the crop took up between 113.7 and 146.5 kg·ha^{-1} (Baran *et al.*, 2011).

In the experiment reported by Wrońska *et al.* (2007), increased doses of N (from 80 to 160 kg·ha^{-1}) resulted in a 10% increase in the uptake of Ca by maize. Meller and Bilenda (2013) found out that maize fertilised with NPK took up 35.6 kg Ca·ha^{-1}, and when fertilised with biomass ash, the uptake was 62.5 kg Ca·ha^{-1}. In another study, depending on a maize cultivar, the Ca uptake by maize varied from 27.3 to 30.5 kg·ha^{-1} (Baran *et al.*, 2011). In addition, the type and application method of fertilisers differentiated the uptake of Ca by maize, which then ranged from 25.9 (broadcast fertilisation with Polifoska 6) to 31.5 kg·ha^{-1} (row fertilisation with ammonium phosphate).

Depending on a maize cultivar, the removal of Mg with maize aerial biomass ranged from 19.4 to 23.9 kg·ha^{-1} (Baran *et al.*, 2011). The application method and type of phosphorus containing fertiliser also modified the removal of Mg with maize yield. When N doses were elevated from 80 to 160 kg·ha^{-1}, the uptake of Mg increased by over 13% (Wrońska *et al.*, 2007). Zinc fertilisation also stimulated the accumulation of Mg in maize aerial biomass. In the study carried out by Meller and Bilenda (2013), maize fertilised with mineral fertilisers took up 48.3 kg Mg·ha^{-1}, but this amount increased to 58.5 kg Mg·ha^{-1} after the maize had been fertilised with biomass ash.

Siwik-Ziomek and Lemanowicz (2011) showed that maize for silage grown without fertilisation took up 16 kg S·ha^{-1}, but when fertilised with 80 Mg·ha^{-1} of manure and 90 kg N·ha^{-1} it took up three-fold more sulphur (48.5 kg·ha^{-1}). The experiment conducted by Iżewska and Wołoszyk (2015) demonstrated that much more N and P were removed with grain and straw yields of maize supplied with mineral fertilisers and ash, but a reverse relationship was proved for sulphur.

The fertilisation applied did not have a significant effect on the quantity of P (6.14–6.82 kg P) taken up by maize to produce 1 Mg of grain alongside the corresponding amount of straw (Tab. 5). However, there were significant differences in the uptake of P per unit of yield between the years of the experiment. The highest unit uptake of P (5.23 kg P·Mg^{-1}) occurred in the first year of the study, which was characterised by a large rainfall deficit and the smallest yield of grain and straw. In the second year, when the meteorological conditions promoted good maize yields, maize took up 8.67 kg P·Mg^{-1} of grain and the appropriate amount of straw. The data found in the available literature suggest that the uptake of P per yield unit tended to be lower than in our study. Grzebisz and Gaj (2007) determined the uptake of P by maize per yield unit to be within the range of 4.0 to 4.5 kg·Mg^{-1}, and Jadczyszyn (2006) suggested it was 5.4 kg P. In a study by Wrońska *et al.* (2007), depending on a nitrogen dose, maize took up between 4.61 and 4.79 kg P·Mg^{-1} of grain. Maize fertilised with zinc took up around 10% less P to produce 1 Mg of grain with the corresponding amount of straw than maize grown without zinc nutrition.

The unit uptake of K was within the range of 23.12–27.61 kg·Mg^{-1} of grain, and the tested fertilisers did not have a significant effect on the uptake volume. The significantly highest amount of K (30.32 kg·Mg^{-1}) was taken up by maize growing under the weather conditions that favoured good yielding, that is in the 2nd research year, while the lowest uptake (22.27 kg·Mg^{-1}) appeared in the excessively wet 3rd year (Tab. 5). Grzebisz and Gaj (2007) determined the K uptake at the level of 15 to 20 kg·Mg^{-1} of grain. Slightly higher uptake is given by Jadczyszyn (2006) – in her experiment, the K uptake per yield unit was 23.3 kg·Mg^{-1}. Wieremiej (2016) concluded that the unit uptake of K depended on fertilisation. Maize grown without fertilisation took up 12.11 kg K·Mg^{-1} of grain, but this amount increased to 24,27 kg·Mg^{-1} when the crop had been fertilised. According to Wrońska *et al.* (2007), the level of N fertilisation had little impact on the uptake of K per yield unit, which she determined to range between 14.17 and 14.63 kg·Mg^{-1}.

The uptake of Ca per unit of yield was from 5.09 (UAN/urea) to 6.20 kg·Mg^{-1} ((UAN + P(Starter))/(UAN + Mg)), and the tested fertilisation did not have a significant influence on this parameter (Tab. 5). The significantly highest uptake of Ca per unit of (7.12 kg·Mg^{-1}) took place in the second year of the experiment, when maize produced the highest grain and straw yields. In the third year, when rainfalls were abundant, maize took up only 3.97 kg Ca to produce 1 Mg of grain. A much lower Ca

Table 5. Uptake of macronutrients by maize per 1 Mg of grain with an adequate amount of straw in kg·Mg^{-1} (mean ±standard deviation)

Specification	Uptake of				
	P	K	Ca	Mg	S
Average for fertilisation					
Control, no nitrogen fertilisation	6.16 ±1.42	24.84 ±3.82	5.89 ±1.72	3.60 ±0.96	2.97^{a} ±0.52
Ammonium nitrate/urea	6.36 ±1.77	25.79 ±7.17	5.59 ±1.60	3.22 ±0.66	2.66^{ab} ±0.27
UAN/urea	6.16 ±1.64	24.38 ±4.38	5.09 ±1.24	3.20 ±0.45	2.42^{b} ±0.16
UAN/UAN	6.14 ±1.34	26.98 ±3.41	5.49 ±1.09	3.44 ±0.93	2.93^{a} ±0.37
(UAN + S)/(UAN + Mg)	6.76 ±2.11	24.97 ±5.99	5.68 ±2.06	3.36 ±0.75	2.85^{ab} ±0,42
(UAN + P(Medium))/(UAN + P(Medium))	6.50 ±1.70	23.12 ±4.65	5.25 ±1.16	3.08 ±0.53	2.85^{ab} ±0.23
(UAN + P(Starter))/(UAN + S)	6.53 ±1.70	25.53 ±6.42	5.69 ±1.74	3.25 ±0.53	2.89^{a} ±0.22
(UAN + P(Starter))/(UAN + Mg)	6.82 ±2.05	27.61 ±5.11	6.20 ±1.93	3.37 ±0.59	2.82^{ab} ±0.37
Average for years of study					
2015	5.23^{A} ±0.38	23.62^{A} ±4.04	5.74^{B} ±0.99	4.10^{C} ±0.52	3.05^{C} ±0.47
2016	8.67^{B} ±0.82	30.32^{B} ±4.69	7.12^{C} ±1.18	3.18^{B} ±0.23	2.77^{B} ±0.24
2017	5.38^{A} ±0.29	22.27^{A} ±2.74	3.97^{A} ±0.31	2.67^{A} ±0.16	2.58^{A} ±0.13

Explanations: data marked with different letters differ significantly at $p < 0.05$.
Source: own study.

uptake per yield unit (2.56–2.66 kg Ca·Mg^{-1} of grain) was noted by Wrońska *et al.* (2007).

In this experiment, the uptake of Mg per yield unit was similar to amounts given in the literature. Maize took up from 3.08 to 3.60 kg of magnesium to produce 1 Mg of grain with the corresponding quantity of straw, and the applied fertilisation had no significant effect on this parameter (Tab. 5). Comparison of the year-average data showed that the lowest magnesium uptake per yield unit (2.67 kg·Mg^{-1}) appeared in the very wet 3rd year of the experiment, while the highest one (4.10 kg·Mg^{-1}) took place in the 1st year, when the maize grain and straw yields were the lowest. According to Grzebisz and Gaj (2007), the uptake of Mg by maize depended on the yield, and ranged from 3.0 to 4.0 kg·Mg^{-1} of grain. Wrońska *et al.* (2007) recorded the uptake of magnesium from 2.24 to 2.43 kg·Mg^{-1} of grain.

The significantly highest uptake of S per yield unit was demonstrated by maize grown without nitrogen fertilisation (2.97 kg S·Mg^{-1}); in turn, fertilisation with UAN/urea resulted in maize taking up 2.42 kg S to produce 1 Mg of grain and associated straw (Tab. 5). The significantly lowest uptake of this element per 1 Mg of grain (2.58 kg·Mg^{-1}) and associated straw was determined for maize grown in the wet, third year of the study, while the highest uptake (3.05 kg·Mg^{-1}) occurred in the first year. The same parameter determined by Grzebisz and Gaj (2007) ranged from 2.60 to 2.25 kg·Mg^{-1} of grain and associated straw, depending on maize yields (grain yield of 5 and 8 Mg·ha^{-1}, respectively).

Such elements as P and Mg mostly accumulate in maize grain, whereas K and Ca are mostly contained in vegetative organs. Significant differences in the contribution of grain to the accumulation of macronutrients appeared between the three experimental years (Fig. 3). The share of grain in the accumulation of P was on average 55% (2nd year) up to 71% (3rd year). The significantly highest share of grain in K accumulation (24%) was revealed in the 3rd year, while being equal 15–16% in the other years. Same as K accumulation, the significantly highest contribution of grain to the accumulation of Ca (~15%) was observed in the 1st year; it then fell to slightly more than 12% in the subsequent years. Unlike P accumulation, the highest share of grain in the accumulation of Mg (~60%) was noted in the 2nd year of the experiment. The least Mg (~40%) was accumulated by maize grain in the 3rd year. The share of maize grain in the accumulation of S varied from ~48–59%. The significantly most of this element was accumulated by maize grain in the 3rd year, while the least was accumulated in the 1st year of the experiment.

The significantly lowest contribution of maize grain to P accumulation was noted in maize from the control and from the plots fertilised with UAN before sowing and by top-dressing (61 and 62%, respectively), while the highest (~69%) was achieved by maize fertilised with UAN/urea (Fig. 4). The significantly lowest contribution of grain to K accumulation (~17%) was found after fertilising maize twice with UAN or with (UAN + P (Starter))/(UAN + Mg). The most of this element (~21%) was accumulated by grain from the UAN/urea fertilisation treatment. The tested fertilisation did not have a significant effect on the contribution of grain to the accumulation of Mg (45–53%) or Ca (11–14%). The significantly lowest (47%) contribution of grain to the accumulation of S was determined in control maize.

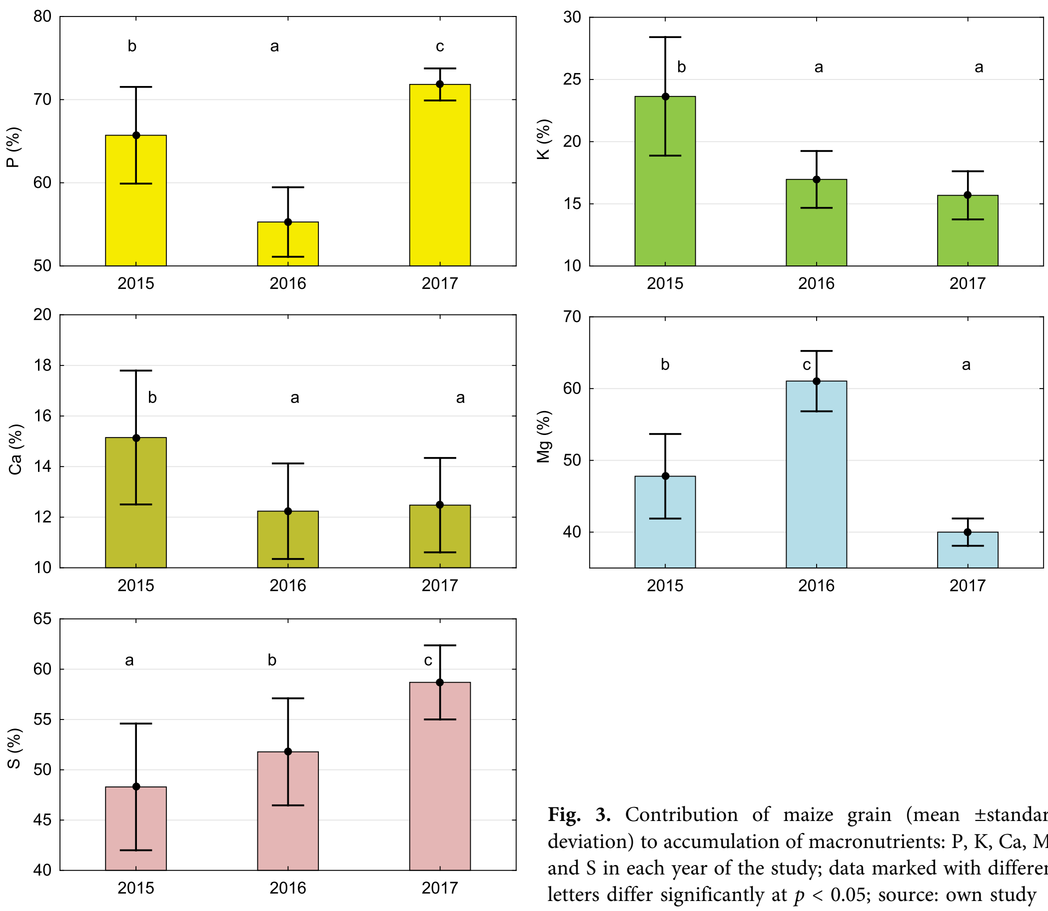

Fig. 3. Contribution of maize grain (mean ±standard deviation) to accumulation of macronutrients: P, K, Ca, Mg and S in each year of the study; data marked with different letters differ significantly at $p < 0.05$; source: own study

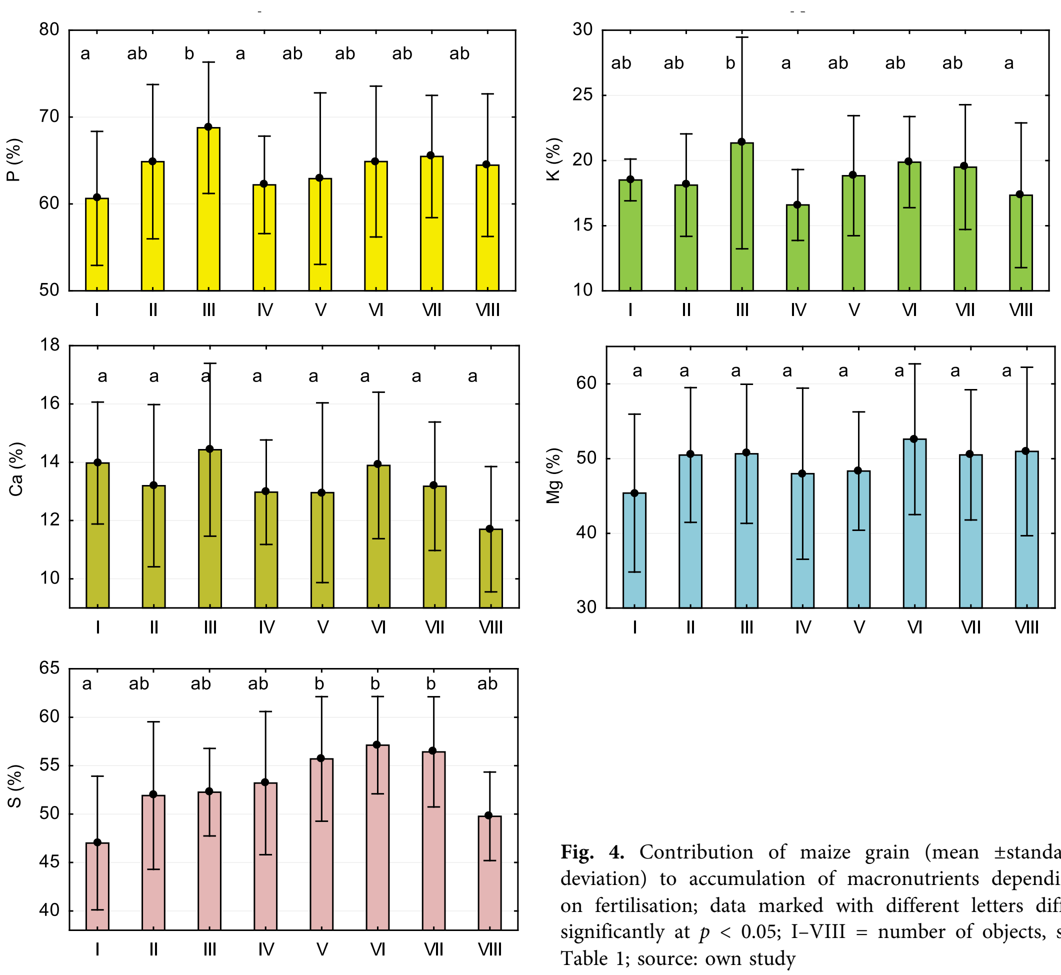

Fig. 4. Contribution of maize grain (mean ±standard deviation) to accumulation of macronutrients depending on fertilisation; data marked with different letters differ significantly at $p < 0.05$; I–VIII = number of objects, see Table 1; source: own study

Significantly more S (56–57%) was accumulated by the grain of maize fertilised before sowing or by top-dressing with UAN + S (treatments (UAN + S)/(UAN + Mg), (UAN + P(Starter))/(UAN +S)) or twice with UAN + P(Medium).

In their study, Ray *et al.* (2020) showed that maize grain accumulated between 59 and 74% of total accumulated P, depending on a maize variety and level of NPK fertilisation. In turn, the contribution of grain to K accumulation depended on the year of the experiment, and varied between 27 and 32%. According to Baran *et al.* (2011), the share of maize grain in the accumulation of P was as high as 78%, while its contribution to the accumulation of a K, Ca and Mg was 36.0; 1.0 and 15.0%, respectively. Wieremiej (2016) concluded that, depending on fertilisation, the contribution of grain to the accumulation of P was 36–83%, and reached 30% of all K taken up by the plant. Over 50% of Mg and ~13% Ca taken up by maize were accumulated in grain (Gaj *et al.*, 2018).

CONCLUSIONS

The effects of the fertilisation variants on the content of macronutrient in maize grain and straw were demonstrated in every year of the study, but the year-average data showed that the significant impact of fertilisation was verified only with respect to P and S in grain and on K and Ca in straw.

Due to the highly different yield volumes obtained in every year of this experiment, the uptake and removal of P, K, Ca, Mg and S with maize mostly depended on maize grain and straw yields. Depending on the year of the study, the amount of nutrients was strongly differentiated and amounted in kg·ha^{-1}: P – from 35 to 100, K – from 150 to 350, Ca – from 40 to 80, Mg – from 25 to 35 and S – from 20 to 31. However, fertilisation also had some significant effects. Significant differences were detected in terms of the removal of P, K, Mg and S. The significantly least of these elements per megagram of grain and associated straw amount was taken up by maize grown in the extremely rainy third year. Only the uptake of sulphur per yield unit that was significantly different depending on fertilisation. The contribution of grain to the accumulation of nutrients was also significantly differentiated in the three years of the study. The significantly lowest share of grain in the accumulation of P and S was noted in unfertilised maize (control). The tested fertilisation had no significant effect on the contribution of grain to the accumulation of Mg and Ca.

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