Journal of Elementology ISSN 1644-2296

Jankowski K.J., Sokólski M. 2018.
The effect of a micro-granular starter fertilizer on the biomass quality of winter oilseed rape.
J. Elem., 23(4): 1243-1255. DOI: 10.5601/jelem.2018.23.1.1634

RECEIVED: 21 February 2018
ACCEPTED: 22 May 2018

ORIGINAL PAPER

THE EFFECT OF A MICRO-GRANULAR STARTER FERTILIZER ON THE BIOMASS QUALITY OF WINTER OILSEED RAPE*

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Abstract

The effectiveness of mineral fertilization can be improved through starter or band application. This technique reduces fertilizer doses (costs) and minimizes environmental risks (decreased nutrient stratification, reduced nutrient emissions to surface water, groundwater and the ambience). This paper presents the results of a 3-year study investigating the effects of a micro-granular starter fertilizer (MSF) applied in the seed zone on the macronutrient content in autumn and after the harvest of winter oilseed rape (*Brassica napus* L.). The study was carried out at the Agricultural Experimental Station in Bałcyny (northeastern Poland) in 2012-2015. The application of MSF, in addition to NPK applied pre-sowing (NPK + MSF), contributed to an increase in the macronutrient content of leaf rosettes (N, P, K and Ca) and roots (N, P and K) of winter oilseed rape before the end of the growing season. The application of MSF in treatments with NPK fertilization significantly decreased the content of P and Mg in the seeds of winter oilseed rape. The application of MSF increased the macronutrient content of straw, but the magnitude of this effect was determined by the NPK dose applied pre-sowing. The application of MSF (regardless of NPK doses) increased the content of N, P, Mg and Ca, and decreased the content of K in the roots of winter oilseed rape. *In treatments where MSF was combined with a standard dose of NPK applied pre-sowing, the* nutrient uptake increased by 12-24% N, 14-22% P, 13-26% K, 11-24% Mg and 18-24% Ca (75-90 days after sowing (DAS). The application of MSF increased the macronutrient uptake by straw, but decreasedthe macronutrient uptake by roots (318-332 DAS).

Keywords: *Brassica napus*, nutrients, starter fertilizer.

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* The results presented in this paper were obtained as part of a comprehensive study financed by the University of Warmia and Mazury in Olsztyn and Timac Agro Poland Ltd in Niepruszewo (Projects No. 20.610.020-300 and 20.690.010-500).

INTRODUCTION

Mineral fertilizers are widely used in agriculture to maintain soil fertility and increase crop yields. Their application has been increasing since the beginning of the 20th century. Fertilization is one of the main yield-forming factors in the production of strategic commercial crops. For this reason, fertilizers, in particular inorganic ones, play an important role in the global food supply (Gilland 2002). In 1920-1960, the use of phosphorus fertilizers exceeded the use of nitrogen and potassium fertilizers. The popularity of nitrogen fertilizers increased substantially after 1960. At present, the use of nitrogen fertilizers is 2.7-fold higher in comparison with phosphorus fertilizers and nearly 4-fold higher in comparison with potassium fertilizers. The total consumption of mineral fertilizers has increased nearly 100-fold since 1920 (Allen 1997, Dale et al. 2000, Roberts 2009).

In intensive farming, growing amounts of fertilizers are unlikely to drive a further increase in crop yields. Yields can be improved only by maximizing the efficiency of nutrient uptake and utilization. This can be achieved by adapting: (i) fertilizer doses to the specific nutrient requirements of various crops, and (ii) the fertilizer application period to the growth stages and nutrient requirements of crops (Roberts 2007).

According to Furness (2007), modern agriculture benefits from research investigating nutrient content in soil and the nutritional status of crops as well as GPS and GIS technologies which increase the precision of fertilizer application. These techniques support the development of digital soil maps, and they contribute to advances in effective methods of fertilizer placement, including starter and band application. Precision fertilization and methods where the dose and date of application are adapted to the specific requirements of the produced crops can improve nutrient utilization by 30% (Górecki 2002). Although the current progress in fertilizer technology is difficult to implement into agricultural practice (Piwowar 2011), starter fertilization is widely used in selected regions of the USA (Bermudez, Mallarino 2004). In starter fertilization, small amounts of fertilizers are applied directly in the seed zone or in between seed rows (Hergert et al. 2006). This application method increases the content of relatively immobile nutrients in the rhizosphere (Barber, Kovar 1985). Nutrients stimulate the root growth and increase plant ability to take up nutrients from deeper soil horizons. The accelerated growth increases the resistance of young plants to diseases and pests, and maximizes their ability to compete with weeds (Beegle et al. 2003).

The objective of this study was to determine the effect of a micro-granular starter fertilizer (MSF) applied in the seed zone of winter oilseed rape on the content and uptake of macronutrients in autumn, and their accumulation in the harvested biomass.

MATERIALS AND METHODS

Experimental site

The experiment was conducted in 2012-2015, at the Agricultural Experimental Station in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, elevation of 137 m) in northeastern Poland. The station belonged to the University of Warmia and Mazury in Olsztyn. The experiment involved the following autumn fertilization treatments: (i) 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} (NPK); (ii) 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} of a micro-granular starter fertilizer (NPK+MSF); (iii) 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + 25 kg ha^{-1} MSF (½ NPK + MSF), (iv) only 25 kg ha^{-1} MSF. NPK fertilizers were applied 3-4 days before sowing and were mechanically incorporated into the soil to a depth of 5-8 cm. Nitrogen was applied in the form of ammonium nitrate (34% N), P was applied as enriched superphosphate (17% P), and K – as potash salt (60% K). The Physiostart® micro-granular starter fertilizer with a granule diameter of 6-8 mm contained 8% N (NO_3-N only), 12% P, 10% Ca, 9% S and 2% Zn. It was distributed with the use of a precision seeder equipped with a fertilizer applicator. The fertilizer was placed in the immediate vicinity of sown seeds.

In spring, all treatments were fertilized with 220 kg N ha^{-1} in two applications: 120 kg N ha^{-1} in the form of ammonium nitrate (34% N) and ammonium sulfate (21% N and 24% S) at the beginning of the growing season, and 100 kg N ha^{-1} in the form of ammonium nitrate (34% N) at the beginning of bud formation. 45 kg S ha^{-1} was applied with the first dose of N (ammonium sulfate, 21% N and 24% S).

Experimental design and crop management

The experiment had a randomized complete block design with three replications. The plot size was 25.2 m^2 (7.2 m × 3.5 m). Each year, the experiment was established on Haplic Luvisol developed from boulder clay (IUSS 2006). The content of C_{org}, plant-available P, K, Mg, -S, Cu, Zn, Mn, Fe, and pH in mol dm^3 KCl were determined in the 0-30 cm soil horizon before the experiment. Soil samples were collected from three horizons (0-30, 30-60 and 60-90 cm) before the experiment to determine the content of mineral nitrogen (NH_4-N and NO_3-N) – Table 1. The content of NH_4-N in the soil was determined colorimetrically with Nessler's reagent, and NO_3-N levels were determined colorimetrically with phenoldisulfonic acid. Soil organic C was determined using the Kurmies' modified method. Soil pH was measured using a digital pH meter with temperature compensation (20°C) in deionized water and 1 mol dm^3 KCl at a 5:1 ratio. Plant-available P and K were measured by the Egner-Riehm method (using 3.5 mol ammonium lactate acetic acid buffered to pH = 3.75 as extracting solution). Phosphorus was determined by the vanadium molybdate yellow colorimetric method, and K was determined by atomic emission spectrometry (AES). Magnesium was extracted

Table 1

Chemical properties of the analyzed soil

Years	pH (1 mol dm^3 KCl)	C_{org} (%)	$N-NO_3$ ($mg\ kg^{-1}$)			$N-NH_4$ ($mg\ kg^{-1}$)			Available macronutrients and micronutrients ($mg\ kg^{-1}$)							
			I†	II	III	I	II	III	P	K	Mg	SO_4^{2-}	Cu	Zn	Mn	Fe
2012/13	5.52	0.89	9.88	4.77	1.98	2.67	1.73	1.53	60.1	110.1	71	8.3	2.8	18.6	191	2380
2013/14	6.08	1.08	9.71	7.41	5.40	1.57	1.02	1.50	77.2	212.4	62	7.5	2.0	17.9	189	2200
2014/15	6.36	0.89	4.19	0.29	3.35	5.05	0.75	1.52	71.5	98.9	90	11.1	3.8	21.6	198	2450

† soil horizon: I - 0-30 cm, II - 31-60 cm, III - 61-90 cm

with 0.01 M $CaCl_2$ and determined by atomic absorption spectrophotometry (AAS). Micronutrients (Cu, Zn and Mn) were extracted with 1 M HCl and determined by AAS after extraction in 1 mol dm^3 HCl. The content of -S was determined by nephelometry after extraction in acetate buffer.

The preceding crop in each year of the study was winter triticale (×*Triticosecale* Wittm. ex A. Camus.). Winter rapeseed hybrid cv. SY Kolumb (canola type) was sown between 17 and 20 August at 33 pure live seeds m^{-2} and inter-row spacing of 45 cm. Growth regulator (37.5 g ha^{-1} paclobutrazol and 75 g ha^{-1} difenoconazole) was applied in the 4-6 leaf stage. Weeds were controlled with 832.5 g ha^{-1} metazachlor and 207.5 g ha^{-1} quinmerac after sowing. The following insecticides were applied four times in spring: the organophosphate insecticide chlorpyrifos at 288 g ha^{-1}, the neonicotinoid insecticide acetamiprid at 24 g ha^{-1}, and two pyrethroid insecticides – deltamethrin at 5 g ha^{-1}, and alpha-cypermethrin at 12 g ha^{-1}. Pathogens were controlled with dimoxystrobin at 100 g ha^{-1} and boscalid at 100 g ha^{-1} in the full flowering stage (BBCH 65). Winter oilseed rape was harvested in the fully ripe stage (BBCH 89) with a small-plot harvester (mid-July).

Plant analysis

Samples of leaf rosettes were collected before the end of the growing season (75 days after sowing (DAS) during the seedling stage in 2012/2013, 81 DAS in 2012/2013, and 90 DAS in 2014/2015) from 20 randomly selected plants in each treatment. The sampled plants (aerial rosette parts and roots) were dried at a temp. of 70°C for 72 h (Binder drying oven, Germany) to determine their dry matter content. Samples of mature plants were collected immediately before threshing (332 DAS in 2012/2013, 318 DAS in 2013/2014, and 322 DAS in 2014/2015) from 20 randomly selected plants in each treatment. Root weight was determined immediately after harvest at three random points in each plot. Soil was sampled into a steel cylinder measuring 22.57 cm in diameter and 30 cm in length. Soil and root samples were rinsed with water in a 1 mm mesh sieve. The dry matter content of roots was determined by drying at a temp. of 70°C for 72 h (Binder drying oven, Germany).

Chemical composition of plants

The macronutrient content of plants was determined on a dry weight basis. Dried plants were ground in a laboratory mill (GM 300, Retsch, Germany). Their phosphorus content was determined by the vanadium-molybdenum method, Ca and K – by atomic emission spectrometry (AES), Mg – by AAS, total N – by the hypochlorite method. Nutrient uptake was calculated based on plant biomass expressed on a dry matter (DM) basis and nutrient content.

Statistical analysis

Data were analyzed by ANOVA, and treatment means were compared by the Duncan's test at a probability level of 0.05 using Statistica 10.1 PL (StatSoft, Inc. 2011).

RESULTS AND DISCUSSION

Nutrient accumulation in winter oilseed rape plants in autumn

The content of cryprotectants increases, whereas the water content of plant tissues decreases in autumn. Overwintering success is maximized in plants that have developed deep and extensive root systems with a root crown diameter larger than 1 cm, as well as rosettes with 8-10 leaves. In winter oilseed rape, dry matter is most intensely accumulated upon the achievement of the 5 leaves unfolded stage. Intensive physiological processes, including the accumulation of nutrients in vital plant organs, take place at this stage (Velička et al. 2012). The above processes require an adequate supply of P, which stimulates the root growth (lateral roots and root hairs, mycorrhizal symbiosis), Mg and K which regulate carbohydrate metabolism, as well as S and Cu which control the synthesis of structural carbohydrates – cellulose and lignin (Maathuis 2009).

Localized fertilization can stimulate plant growth, induce structural and morphological changes in roots and influence the uptake of water and dissolved nutrients (Nosalewicz 2013). A study conducted in central China (Su et al. 2015) revealed an increase in the N and P content of rosette leaves (76 DAS) when a dose of localized fertilizer was increased by 7.1 and 0.4-1.9 g kg^{-1} DM, respectively.

In the present study, rosette leaves accumulated 5-fold more Ca, two-fold more N, 1.4-fols more K and 1.5-fold more Mg than roots. The application of NPK fertilizer with MSF increased the macronutrient content of rosette leaves by: 3.2-5.5 g N kg^{-1} DM, 0.3-0.5 g P kg^{-1} DM, 4.3-5.4 g K kg^{-1} DM, and 2.6-5.0 g Ca kg^{-1} DM in comparison to other objects (Table 2).

In autumn, the roots of winter oilseed rape also accumulated the highest amounts of N (24.2 g kg^{-1}), P (5.5 g kg^{-1}) and K (30.7 g kg^{-1}) in the NPK+MSF treatment. In the remaining treatments (NPK, ½ NPK + MSF, MSF), the N, P and K content of roots decreased by 2.7-4.5, 0.5-0.2 and 2.0-3.0 g kg^{-1} DM, respectively (Table 2).

Su et al. (2015) demonstrated that winter oilseed rape accumulated 79-136 kg N ha^{-1}, 6-12 kg P ha^{-1} and 67-118 kg K ha^{-1} to produce healthy rosette leaves in autumn (76 DAS). When applied to a depth of 10 and 15 cm, NPK fertilizers (urea, calcium superphosphate, potassium chloride) increased N uptake by 80%, K uptake by 82%, and P uptake by 100%.

In the present study, the macronutrient uptake (N, P, K, Mg, Ca) by

Table 2

The influence of autumn fertilization on the macronutrient (g kg^{-1} DM) content of winter oilseed rape plants in autumn across years

Nutrient	Fertilization†			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Leaf rosettes				
N	43.0^{b}	46.2^{a}	41.8^{bc}	40.7^{c}
P	5.1^{b}	5.5^{a}	5.2^{b}	5.0^{c}
K	37.8^{b}	43.1^{a}	38.8^{b}	37.7^{b}
Mg	3.0	3.0	2.7	2.5
Ca	20.7^{b}	23.3^{a}	19.1^{bc}	18.3^{c}
Roots				
N	21.5^{b}	24.2^{a}	23.1^{ab}	19.7^{c}
P	5.3^{ab}	5.5^{a}	5.5^{a}	5.0^{b}
K	27.7^{b}	30.7^{a}	28.7^{ab}	28.7^{ab}
Mg	1.8	1.8	1.7	1.7
Ca	3.5^{c}	4.0^{b}	4.4^{a}	3.9^{b}

† NPK: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1}; NPK + MSF: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} MSF; ½ NPK + MSF: 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + 25 kg ha^{-1} MSF; MSF: 25 kg ha^{-1} MSF.
Means with the same letters do not differ significantly at $P \leq 0.05$ in the Duncan's test.
MSF – micro-granular starter fertilizer

winter oilseed rape in autumn ranged from 128 to 155 kg ha^{-1}. The predominant macronutrients assimilated in autumn were N (39-40%, 46-61 kg ha^{-1}), K (36-38%, 43-58 kg ha^{-1}) and Ca (15-16%, 19-25 kg ha^{-1}) – Table 3. In all analyzed seasons, MSF had a positive influence on macronutrient uptake by winter oilseed rape plants during the autumn growth period. The nutrient uptake was particularly high in treatments where MSF was combined with the NPK fertilizer applied pre-sowing (NPK+MSF). In those treatments, nutrient uptake levels were estimated at 60.6 kg N ha^{-1}, 57.7 kg K ha^{-1}, 24.7 kg Ca ha^{-1}, 7.9 kg P ha^{-1} and 3.7 kg Mg ha^{-1}. In treatments where the NPK fertilizer was applied at half the dose or was not applied (½ NPK + MSF or MSF only) and in treatments where MSF was not applied (NPK only), the nutrient uptake was reduced by 12-24% N, 14-22% P, 13-26% K, 11-24% Mg and 18-24% Ca (Table 3).

Nutrient accumulation in the harvested biomass

In the current study, winter oilseed rape seeds were most abundant in N (32.4-35.2 g kg^{-1} DM). The content of the remaining macronutrients was 3- to 6-fold lower (P, K) and 7- to 11-fold lower (Ca, Mg) on average than N content. Straw was most abundant in Mg (12.3 g kg^{-1} DM on average).

Table 3

The influence of autumn fertilization on macronutrient (kg ha^{-1}) uptake by winter oilseed rape plants (rosettes + roots) in autumn across years

Nutrient	Fertilization†			
	NPK	NPK + MSF	½ NPK + MSF	MSF
N	46.0^{b}	60.6^{a}	53.5^{ab}	50.7^{b}
P	6.2^{c}	7.9^{a}	7.3^{ab}	6.8^{bc}
K	42.5^{c}	57.7^{a}	50.0^{b}	48.4^{c}
Mg	3.3^{ab}	3.7^{a}	3.1^{ab}	2.8^{b}
Ca	18.7^{b}	24.7^{a}	20.3^{b}	19.4^{b}
∑	116.7^{b}	154.6^{a}	134.1^{b}	128.1^{b}

† NPK: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1}; NPK + MSF: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} MSF; ½ NPK + MSF: 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + 25 kg ha^{-1} MSF; MSF: 25 kg ha^{-1} MSF.
Means with the same letters do not differ significantly at $P \leq 0.05$ in the Duncan's test.
MSF – micro-granular starter fertilizer

The content of the remaining macronutrients was 2.4-fold (N, K) to 10- and 11-fold lower (P, Ca), compared with Mg. In the fully ripe stage (BBCH 89), the roots of winter oilseed rape were characterized by the highest content of K (25.6 g kg^{-1} DM) and Mg (17.2 g kg^{-1} DM). The content of N, P and Ca in roots was 3-fold, 9-fold and 14-fold lower, respectively, than K levels. Seeds were most abundant in N, P and Ca. The highest content of K and Mg was noted in roots. Roots contained 2 times more K, and 9 times more Mg than seeds (Table 4).

In early spring, the biomass of healthy winter oilseed rape plants is estimated at 1.5-2.5 Mg ha^{-1} DM, and it increases to 14-18 Mg ha^{-1} in the fully ripe stage (100 days after emergence in NE Poland). In stage BBCH 89, the accumulation of nutrients in plant biomass is determined by a combination of natural and agronomic factors (mainly fertilization) (Jankowski 2007).

In the present experiment, no significant differences in the N and Ca content of seeds were observed across fertilization treatments. The content of the remaining macronutrients (P, K, Mg) in seeds was highest in response to standard NPK fertilization. The application of MSF with a standard dose of NPK significantly reduced the P and Mg content of seeds (Table 4).

The application of MSF increased the macronutrient content of straw, but the magnitude of this effect was determined by the NPK dose applied pre-sowing. The application of NPK decreased the content of N, Mg and Ca (NPK+MSF and ½NPK+MSF), and increased the content of P and K (½NPK+MSF). In roots, the content of N, P, Mg and Ca increased, whereas the content of K decreased in response to MSF (regardless of the NPK rate) – Table 4.

In the fully ripe stage (BBCH 89), K is the predominant nutrient in win-

Table 4

The influence of autumn fertilization on the macronutrient (g kg^{-1} DM) content of the harvested biomass of winter oilseed rape (BBCH 89) across years

Nutrient	Fertilization†			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Seeds				
N	34.6	32.4	34.4	35.2
P	10.2^{a}	9.3^{bc}	9.2^{c}	9.5^{b}
K	7.2^{a}	6.9^{a}	6.8^{a}	6.1^{b}
Mg	5.1^{a}	4.5^{d}	4.7^{c}	4.9^{b}
Ca	3.2	3.1	3.2	3.1
Straw				
N	5.1^{b}	4.9^{bc}	4.8^{c}	5.8^{a}
P	1.1^{b}	1.1^{b}	1.2^{a}	0.8^{c}
K	3.7^{d}	5.0^{c}	6.1^{a}	5.6^{b}
Mg	9.9^{d}	12.6^{b}	10.9^{c}	15.8^{a}
Ca	0.8^{c}	1.0^{b}	0.9^{b}	1.8^{a}
Roots				
N	7.7^{b}	7.4^{bc}	9.0^{a}	7.3^{c}
P	1.6^{b}	4.2^{a}	4.2^{a}	1.8^{b}
K	30.8^{a}	26.3^{b}	24.2^{c}	21.1^{d}
Mg	17.5^{b}	16.6^{bc}	18.5^{a}	16.4^{c}
Ca	1.6^{b}	1.8^{a}	1.9^{a}	1.6^{b}

† NPK: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1}; NPK + MSF: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} MSF; ½ NPK + MSF: 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + 25 kg ha^{-1} MSF; MSF: 25 kg ha^{-1} MSF.
Means with the same letters do not differ significantly at $P \leq 0.05$ in the Duncan's test.
MSF – micro-granular starter fertilizer

ter oilseed rape (seeds and straw), and its accumulation exceeds that of N in high-producing plantations. The average accumulation of K in seeds reaches 66 kg Mg^{-1} (with the equivalent straw yield). Winter oilseed rape plants also accumulate N (60 kg Mg^{-1}), Ca (50 kg Mg^{-1}) and P (13 kg Mg^{-1}) (Tys et al. 2003). In our study, around 51% of macronutrients were stored in seeds, 31% in straw, and 18% in roots (Table 5). In the present study, nitrogen was accumulated in 77% in seeds, in 16% in straw, and in 7% in roots. The distribution of P and Ca in the harvested biomass was similar (79% and 58% in seeds, 12% and 30% in straw, and 9% and 12% in roots, respectively). Potassium and Mg were accumulated mainly in the vegetative organs of winter oilseed rape. The highest potassium accumulation was noted in roots (41%), followed by straw (31%) and seeds (28%). Magnesium was stored mostly in straw (61%) – Figure 1.

Table 5

The influence of autumn fertilization on macronutrient (kg ha^{-1} DM) uptake by winter oilseed rape plants (89 BBCH) across years

Nutrient	Fertilization†			
	NPK	NPK + MSF	½ NPK + MSF	MSF
Seeds				
N	174.1	175.7	181.4	186.2
P	51.3^{a}	50.4^{ab}	48.5^{b}	50.4^{ab}
K	36.3^{a}	37.5^{a}	35.9^{a}	32.4^{b}
Mg	25.5	24.6	24.7	25.7
Ca	16.2	16.5	16.6	16.3
∑	303.4	304.8	307.1	310.9
Straw				
N	34.6^{c}	39.5^{b}	35.8^{c}	42.2^{a}
P	7.5^{b}	8.7^{a}	8.8^{a}	5.9^{c}
K	24.9^{c}	40.1^{b}	45.6^{a}	41.9^{b}
Mg	67.2^{d}	100.8^{b}	82.9^{c}	116.9^{a}
Ca	5.5^{d}	7.7^{b}	7.0^{c}	13.0^{a}
∑	139.7^{d}	196.8^{b}	180.0^{c}	220.0^{a}
Roots				
N	18.7^{a}	13.4^{c}	15.7^{b}	13.9^{c}
P	3.9^{b}	7.5^{a}	7.2^{a}	3.5^{b}
K	74.5^{a}	47.2^{b}	42.2^{c}	40.5^{c}
Mg	42.2^{a}	29.8^{b}	32.0^{b}	31.1^{b}
Ca	4.0^{a}	3.2^{b}	3.3^{b}	3.2^{b}
∑	143.2^{a}	101.2^{b}	100.4^{b}	92.1^{c}

† NPK: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1}; NPK + MSF: 30 kg N ha^{-1}, 35 kg P ha^{-1}, 100 kg K ha^{-1} + 25 kg ha^{-1} MSF; ½ NPK + MSF: 15 kg N ha^{-1}, 17.5 kg P ha^{-1}, 50 kg K ha^{-1} + 25 kg ha^{-1} MSF; MSF: 25 kg ha^{-1} MSF.
Means with the same letters do not differ significantly at $P \le 0.05$ in the Duncan's test.
MSF – micro-granular starter fertilizer

Regardless of an NPK dose, the application of MSF lowered the accumulation of P and K in seeds. The uptake of the remaining macronutrients (N, Ca, Mg) by seeds did not differ significantly between treatments. The application of MSF without NPK increased the accumulation of N, Mg, and Ca in straw. The content of the remaining nutrients was significantly higher in MSF treatments with half the standard NPK dose (P and K). Regardless of an NPK dose, MSF increased P uptake by roots. The uptake of the remaining macronutrients by roots was the highest in treatments with stan-

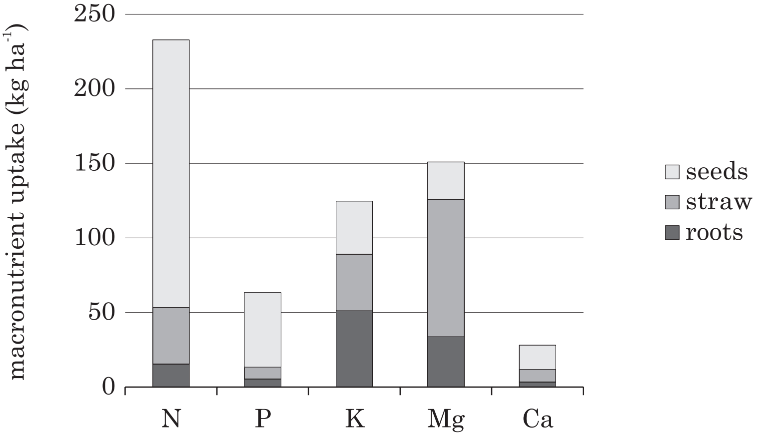

Fig. 1. Macronutrient uptake by winter oilseed rape plants (BBCH 89) across years (means for different methods of fertilizer application in autumn)

dard NPK fertilization without MSF. The application of MSF decreased macronutrient uptake by 29-36% (Table 5).

The overall macronutrient uptake by winter oilseed rape plants was higher in MSF treatments (Table 5). In the work of Su et al. (2015), fertilizer application at a depth of 10-15 cm increased the N, P and K uptake by winter oilseed rape plants in stage BBCH 89 by 54%, 56% and 60%, respectively, in comparison with broadcast fertilizer application. In our study, MSF exerted varied effects on nutrient uptake by the roots, straw and seeds of winter oilseed rape. Irrespective of the NPK doses, MSF significantly decreased the content of P and K in seeds. The application of MSF stimulated the accumulation of macronutrients in straw, and the magnitude of that effect was determined by the rate of NPK applied pre-sowing. In roots, the accumulation of most nutrients (except for P) was reduced in MSF treatments (Table 5).

CONCLUSIONS

1. The application of MSF, in addition to NPK applied pre-sowing, increased the content of N (by 7 and 13%, respectively), P (8 and 4%), K (14 and 11%) and Ca (13 and 14%) in the leaf rosettes and roots of winter oilseed rape before the end of the autumn growing season, but had no influence on Mg accumulation.

2. During the autumn growing season, MSF applied to the seed zone of winter oilseed rape increased macronutrient uptake, by 12-24% N, 14-22% P, 13-26% K, 11-24% Mg and 18-24% Ca.

3. The application of MSF decreased the content of P and Mg in the se-

eds, increased the content of N, P, K, Mg and Ca in the straw, and increased the content of N, P, Mg and Ca in the roots of winter oilseed rape in the fully ripe stage.

4. The application of MSF increased macronutrient uptake by straw, decreased macronutrient uptake by roots, and had no influence on macronutrient accumulation in the seeds of winter oilseed rape.

ACKNOWLEDGMENTS

We would like to thank Dr. Andrzej Kosecki and Andrzej Kerner, Eng. from the Agricultural Experiment Station in Bałcyny for assistance in performing the field experiment.

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