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EFFECT OF MEAT AND BONE MEAL ON THE CONTENT OF MICROELEMENTS IN SOIL, WHEAT GRAINS AND OILSEED RAPE SEEDS*

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Abstract

A possible way to maintain the right level of soil fertility involves using some waste as fertilizer, provided its composition does not violate the pertinent local safety standards. There is currently considerable interest in using meat industry waste, both raw and processed, e.g. meat and bone meal. An experiment on meat and bone meal (MBM) was conducted from 2007-2009 at the research station in Bałcyny (53°36′ N, 19°51′ E), Poland. The aim was to determine the effect of meat and bone meal (MBM) on the content of selected micronutrients in soil as well as in winter and spring wheat grain and in of winter oilseed rape seeds. The effect of MBM fertilizer applied at doses of 1.0, 1.5, 2.0 and 2.5 t ha^{-1} was compared with mineral fertilization or no fertilization. The experiment did not show any effect of the growing MBM doses on the concentration of micronutrients in soil. As a result of using higher doses of MBM (1.5, 2.0 t ha^{-1}), the content of Cu in 2009 and of Zn in 2007 considerably decreased (2.0 and 2.5 t ha^{-1}). Fertilization with MBM at 2.5 t ha^{-1} improved the quality of winter wheat grain by increasing the content of Cu, Fe, Mn and Zn. In most cases, the application of MBM increased the content of micronutrients in the grain of spring wheat and seeds of winter rape, although this has not always been confirmed statistically. An analysis of the micronutrient contents revealed a significant decrease in Zn and Fe in winter wheat grain and in Zn in winter oilseed rape seeds as the content of these elements in the soil increased. Regarding the relationship between the Zn content in soil and in seeds of winter oilseed rape, the coefficient of determination was the closest to the coefficient of linear correlation (R^2 = 0.931). It was only in 2008 that an increase in the Cu content in winter oilseed rape seeds was determined to have increased parallel to an increase in the micronutrient content in soil. Although the chemical content of MBM implicates its good fertilizer value, the study failed to demonstrate a clearly defined impact of the increased MBM doses on the content of the analysed elements in the soil. This may be attributed to the increase in the bioavailable nitrogen forms, which constitute part of the sorption complex. Their bioavailability may also be subject to mutual relationships among elements, which may act antagonistically (Fe and Mn, Ca and Zn).

Keywords: copper, iron, manganese, rape, wheat, zinc.

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INTRODUCTION

A possible way to maintain the right level of soil fertility involves using some waste as fertilizer, provided its composition meets the pertinent local safety standards. There is currently considerable interest in using meat industry waste, both raw and processed, e.g. meat and bone meal – MBM (Jeng et al. 2004, Chen et al. 2011, Bøen, Haraldsen 2013). The use of MBM as a source of nitrogen and phosphorus and its beneficial effect on the yield and biological quality have been researched by Chen et al. (2011), Konopka et al. (2012), Stępień and Wojtkowiak (2013). According to Ylivainio et al. (2007) and Quilty and Cattle (2011), organic fertilizers and different kinds of waste, including MBM, contain nutrients, although these are not readily available to plants and have to be mineralized first. The availability of micronutrients in soil is affected by a number of factors. It depends not only on the amount supplied to the soil as micronutrient fertilizers, but also on the availability of organic matter, microbiological life in soil, the abundance of N and P in soil as well as the soil pH (Singh et al. 2010). Apart from considerable amounts of organic carbon, N and P, MBM contains such micronutrients as copper, zinc, iron and manganese (Jeng et al. 2006; Stępień, Wojtkowiak 2013). The addition of N and P in fertilizers may affect heavy metal management by supporting plant metabolism or changing the form in which heavy metals occur (Sun et al. 2007). As a potential source of calcium, MBM does not raise the soil pH; this may be a result of the activity of microorganisms, whose presence is stimulated by organic waste (Jeng et al. 2006, Stępień 2011). The available literature lacks reports on the content of micronutrients in soil and their availability to plants following the application of MBM. Only Górecka et al. (2009), pursuant to the chemical content of plant material, concluded that the amounts of cadmium, copper, zinc, arsenic, lead and mercury in oilseed rape plants were close to or slightly higher than in the control object. The content of trace elements in the soil exceeded the limit values several times.

The aim of the study was to determine the effect of an application of MBM compared to mineral fertilization and no fertilization on the content of selected micronutrients in soil and grain of winter and spring wheat and seeds of winter oilseed rape.

MATERIAL AND METHODS

Site and experimental design

The findings published in this paper were obtained in a controlled, static field experiment, set up in a randomized complete-block design with 4 replications. The experiment on meat and bone meal was conducted in 2007-2009 at the research station in Bałcyny (53°36′ N, 19°51′ E), Poland. The experiment was carried out on brown soil with the grain-size composition of light loam, classified as *Haplic Cambisol* according to FAO-WRB (2006). The soil texture was that of heavy loamy sand. The physical and chemical soil properties in 2007, before the experiment started, are presented in Table 1.

Table 1

Physical and chemical soil properties before the experiment started in 2007

Measured parameters	Corresponding values
Soil type (FAO 2006)	*Haplic Cambisol*
Soil texture	heavy loamy sand
Soil density (g cm^{-3})	1.36
pH in KCl	5.60
Coherence of soil (MPa)	1.83
Total organic C (g kg^{-1} DM)	10.01
Total N (g kg^{-1} DM)	0.91
P (mg kg^{-1})	85.0
K (mg kg^{-1})	152.4
Mg (mg kg^{-1})	56.3
Cu (mg kg^{-1})	1.49
Mn (mg kg^{-1})	265
Zn (mg kg^{-1})	6.50
Fe (mg kg^{-1})	1823

The experiment in which meat and bone meal was applied every year was conducted for 3 years, with the following crop sequence: 2007 – winter wheat (*Triticum aestivum* L.) var. Oliwin; 2008 – winter rape (*Brassica rapa* L. subsp. *oleifera* (DC.) Metzg.) var. Californium and 2009 – spring wheat (*Triticum aestivum* L.) var. Tybalt. The area of a plot was 24.75 m^2. Sowing, cultivation and harvest were carried out in accordance with the agricultural requirements applicable to the crops under study. Ploughing was conducted down to the depth of 25-30 cm and combined with soil preparation. The farming practices for all the plants consisted of disc ploughing just after harvesting the forecrop. Next, depending on the species, pre-sowing summer-autumn crops preceding to winter wheat and winter oilseed rape were sown or else, in the third part of October, pre-winter ploughing was done for spring wheat. In order to cover up harvest residues prior to sowing winter wheat and winter rape, pre-sowing ploughing and harrowing were done. Shortly prior to sowing winter varieties on all the plots, in order to mix fertilizers (mineral fertilizers and MBM) and to prepare the soil for sowing, a cultivator for sowing and fertilizer systems was applied. The first spring procedure for spring wheat was harrowing, carried out in the first ten days of April. Next, in order to mix mineral fertilizers and MBM and to prepare the soil for sowing, a cultivator for sowing and fertilizer systems was used (cultivator + harrowing + cage roller). The crops were sown uniformly over all the surface of each block, but after the crop emerged the surface divided into 5.5 m x 4.5 m plots by cutting out paths. Weeds were removed only mechanically. In spring, wheat weeds were destroyed by single harrowing with a medium harrow, at the wheat growth stage of 3-4 leaves (BBCH 13-14). In winter wheat, double harrowing was done with a medium harrow. The first harrowing took place in autumn, at the stage of 3-4 leaves (BBCH 13-14), and the second one - in spring, after the wheat had started growing (BBCH 21-29). For winter oilseed rape, weeds were destroyed by single, manual weeding in sprin, after the crop had started growing but prior to forming a shoot (BBCH 31). There were no meaures taken against diseases and pests, except a single spraying of a chemical to eradicate the pollen beetle. This was done in 2008 due to the mass infestation by this pest.

Meat and bone meal (MBM)

The design of the experiment and the doses of nutrients supplied with MBM are presented in Table 2. MBM was applied in doses of 1.0, 1.5, 2.0 and 2.5 t ha^{-1} before sowing each crop. The maximum amounts of MBM did not exceed the permissible amounts, and were in conformity with the Regulation of the Minister of Agriculture and Rural Development of 7 December 2004 (with subsequent amendments) on the veterinary requirements regar-

Table 2

Design of the experiment and doses of nutrients supplied with meat and bone meal (MBM)

Treatments	N	P	K		Mg	Ca	Cu	Zn	Mn	Fe
			MBM	K_{min}*						
	(kg ha^{-1})									
Without fertilization	-	-	-	-	-	-	-	-	-	-
NPK	90.0	31.0	-	83.1	-	-	-	-	-	-
MBM 1.0 t ha^{-1}	66.5	39.8	4.1	83.1	2.0	19.0	0.010	0.099	0.003	0.51
MBM 1.5 t ha^{-1}**	99.8	59.7	6.2	83.1	3.0	28.5	0.015	0.149	0.005	0.77
MBM 2.0 t ha^{-1}**	133.0	79.6	8.2	83.1	4.0	38.0	0.020	0.198	0.006	1.02
MBM 2.5 t ha^{-1}**	166.3	99.5	10.3	83.1	5.0	47.5	0.025	0.248	0.008	1.28

NPK – mineral fertilization, MBM – meat and bone meal
* treatments fertilized with meat and bone meal were additionally supplied with 83.1 kg K ha^{-1};
** the content of compounds in the MBM doses: MBM-1.5 t ha^{-1}, MBM-2.0 t ha^{-1}, and MBM-2.5 t ha^{-1} was generated by converting their content in the MBM dose 1.0 t ha^{-1}

ding soil enrichment additives. The MBM used in the study was in the form of powder, classified into category 3, which comprises animal by-products derived from the manufacture of products intended for human consumption. It was purchased from the Animal By-Products Disposal Plant SARIA Poland. On average, MBM contained 95.5% dry matter; 410.0 g C; 66.5 g N; 42.1 g P; 4.2 g K; 31.0 g Ca and 2.0 g Mg kg^{-1} (DM). Due to small amounts of potassium in MBM (4.2 g), additional potassium at 83.1 kg ha^{-1} K was applied as 49.8% potassium salt. For comparison, a no fertilization control object was created. The following fertilization was applied on the NPK mineral fertilization plots: N – 90 kg ha^{-1} (34% ammonium nitrate); P – 31.0 kg ha^{-1} (triple superphosphate (46%); K – 83.1 kg ha^{-1} (49.8% potassium salt).

Weather conditions

The temperature and precipitation were monitored during the experiment (Table 3). The temperatures and their monthly distribution were similar and did not diverge from the multiannual mean. The total precipitation during the growing season of winter wheat (from September until August in 2006/2007) amounted to 941.9 mm (156% of the multiannual mean), for winter rape (2007/2008) – 545.2 mm (91% of the multiannual mean), and for spring wheat (2009, from April to August) – 334.3 mm (this equalled 55% of the multiannual mean for a whole year). From April to September 2007, precipitation was 29% higher than the multiannual average. In 2008, noteworthy were excessive rainfalls in August (103.1 mm) and October (104.6 mm). In March, May and June 2009, high precipitation, exceeding the mean mul-

Table 3

Weather conditions in Bałcyny in 2006-2009 and the multi-annual average of 1961-2000

Month	Mean air temperature (°C)					Sum of precipitation (mm)				
	2006	2007	2008	2009	1961-2000	2006	2007	2008	2009	1961-2000
January	-8.7	2.4	0.7	-3.7	-1.7	15.3	110.2	30.8	16.2	27.0
February	-3.3	-2.0	2.3	-1.5	-1.5	26.7	14.6	33.9	14.7	22.0
March	-2.5	5.4	2.9	1.9	1.3	3.1	27.9	47.1	68.0	29.0
April	7.8	7.3	7.8	9.7	8.1	24.2	26.8	33.8	3.7	35.0
May	12.5	13.7	12.3	12.2	12.6	93.2	79.7	48.4	89.6	58.0
June	16.0	17.5	16.6	14.7	15.9	83.5	60.8	27.8	133.1	70.0
July	21.0	17.5	18.3	18.9	18.9	27.1	176.5	47.0	82.2	82.0
August	17.3	18.2	17.8	18.5	17.7	141.7	81.0	103.1	25.7	75.0
September	15.7	12.6	11.8	14.7	14.0	105.6	65.4	17.0	15.6	59.0
October	10.1	7.4	8.7	5.9	8.1	34.3	48.9	104.6	58.5	54.0
November	5.6	1.0	4.0	5.2	3.7	107.3	50.0	40.5	40.8	49.0
December	4.2	0.4	-0.1	-1.7	0.4	60.0	9.0	29.4	29.6	42.0
Mean	8.0	8.5	8.6	7.9	8.1					
Sum						722.0	750.8	563.4	577.7	602.0

tiannual value by 39.0 mm, 31.6 mm and 63.1 mm, respectively, was noticed. In contrast, April in the same year was very dry (3.7 mm). However, this did not have any impact on the growing period and moisture conditions, and the decomposition of fertilizers was possible owing to water reserve from March (234% of the multiannual norm).

Sampling, measurements and analyses

Every year, from 2007 to 2009, samples of soil were taken during the plant growing season from the 0-30 cm ploughing layer to assess the main soil micronutrients. The soil was aggregated, dried and passed through a sieve with 1 x 1 mm mesh. Chemical analyses were conducted at a certified laboratory of the District Chemical and Agricultural Station in Olsztyn. Grain/seeds were harvested, dried and cleaned annually during the experiment. Next, the grain/seeds were ground in an IKA A10 laboratory mill (Labortechnik). Micronutrients soluble in 1 m HCl dm^{-3} were extracted by shaking a soil sample in HCl solution at a ratio of 1:10 for 1 hour. Samples of grain and seeds were hot digested in a mixture of HNO_3 and $HClO_4$ mixed at a ratio of 3:1. The content of Cu, Zn, Mn and Fe was determined in the solutions obtained by soil extraction and grain mineralization. The determinations were performed by atomic absorption spectrometry using the flame technique (Panak 1997).

Statistical analyses

The results were statistically processed with software Statistica 10.0 (StatSoft, USA). The statistical calculations were performed with a one-way Anova. Apart from the basic parameters and statistically homogenous groups were determined with Duncan's test at p = 0.05. Linear regression analysis was conducted to determine the relationships between the content of micronutrients in grain/seeds and in soil.

RESULTS AND DISCUSSION

Thus far, the research on the effects of organic material on the content of micronutrients in soil has generated inconclusive results. Several researchers have reported that organic material incorporated into soil raises the soil content of available forms of micronutrients (Iżewska et al. 2009, Wołoszyk et al. 2009, Singh et al. 2010). Brown et al. (2003) found that an addition of organic fertilizers in the form of compost and manure reduced the content of available heavy metal species. Regardless of the fertilization form applied, the highest levels of available micronutrients in the above study were found for iron, and the lowest were detected for copper, i.e. Fe>Mn>Zn>Cu (Table 4). In the current field experiment (Stępień 2011),

Table 4

Micronutrient content in soil (mg kg^{-1})

Treatments	Cu	Zn	Mn	Fe
2007 (winter wheat)				
Without fertilization	$1.40^{a} \pm 0.42$	$7.30^{a} \pm 0.85$	$270^{a} \pm 22.6$	$1718^{a} \pm 196.6$
NPK	$1.45^{a} \pm 0.64$	$6.75^{ab} \pm 0.07$	$244^{a} \pm 12.0$	$1573^{a} \pm 18.4$
MBM 1.0 t ha^{-1}	$1.60^{a} \pm 0.42$	$6.30^{ab} \pm 0.42$	$244^{a} \pm 5.7$	$1557^{a} \pm 9.9$
MBM 1.5 t ha^{-1}	$1.65^{a} \pm 0.35$	$6.55^{ab} \pm 0.21$	$240^{a} \pm 21.2$	$1656^{a} \pm 48.1$
MBM 2.0 t ha^{-1}	$2.00^{a} \pm 0.01$	$5.85^{b} \pm 0.36$	$239^{a} \pm 3.5$	$1530^{a} \pm 195.2$
MBM 2.5 t ha^{-1}	$1.50^{a} \pm 0.42$	$6.00^{b} \pm 0.14$	$239^{a} \pm 1.0$	$1545^{a} \pm 32.3$
2008 (winter rape)				
Without fertilization	$2.10^{a} \pm 0.01$	$7.70^{a} \pm 0.10$	$253^{a} \pm 26.9$	$1648^{a} \pm 203.6$
NPK	$1.40^{a} \pm 0.28$	$8.90^{a} \pm 0.42$	$248^{a} \pm 29.7$	$1747^{a} \pm 188.8$
MBM 1.0 t ha^{-1}	$1.95^{a} \pm 0.78$	$7.05^{a} \pm 1.20$	$214^{a} \pm 17.7$	$1581^{a} \pm 83.4$
MBM 1.5 t ha^{-1}	$2.10^{a} \pm 0.14$	$7.40^{a} \pm 0.99$	$220^{a} \pm 33.9$	$1597^{a} \pm 277.2$
MBM 2.0 t ha^{-1}	$2.25^{a} \pm 0.07$	$7.35^{a} \pm 0.92$	$234^{a} \pm 20.5$	$1662^{a} \pm 149.9$
MBM 2.5 t ha^{-1}	$1.55^{a} \pm 0.21$	$7.90^{a} \pm 1.13$	$206^{a} \pm 19.8$	$1475^{a} \pm 45.3$
2009 (spring wheat)				
Without fertilization	$1.50^{bc} \pm 0.01$	$6.40^{a} \pm 0.28$	$143^{a} \pm 0.7$	$1280^{a} \pm 10.1$
NPK	$1.55^{ab} \pm 0.05$	$7.00^{a} \pm 0.14$	$141^{a} \pm 0.7$	$1285^{a} \pm 91.9$
MBM 1.0 t ha^{-1}	$1.65^{a} \pm 0.07$	$7.35^{a} \pm 0.21$	$148^{a} \pm 6.4$	$1460^{a} \pm 56.6$
MBM 1.5 t ha^{-1}	$1.35^{d} \pm 0.07$	$6.20^{a} \pm 0.42$	$142^{a} \pm 11.3$	$1255^{a} \pm 106.1$
MBM 2.0 t ha^{-1}	$1.35^{d} \pm 0.04$	$7.35^{a} \pm 1.03$	$154^{a} \pm 6.35$	$1485^{a} \pm 62.6$
MBM 2.5 t ha^{-1}	$1.40^{cd} \pm 0.01$	$7.05^{a} \pm 0.70$	$154^{a} \pm 1.4$	$1355^{a} \pm 70.7$

NPK - mineral fertilization, MBM – meat and bone meal
a, *b*, *c*, … values with the same letter are not significantly different according to the Duncan's test ($p \leq 0.05$), ± SD (standard deviation)

after the application of increasing MBM doses, the values of pH or the content of organic C, bioavailable K and Ca did not show any statistically significant changes. With the increasing dosage of MBM at every 0.5 t ha^{-1}, the bioavailable phosphorus content in the soil grew proportionally. In the same research, the increasing doses of MBM (1.5, 2.0, 2.5 t ha^{-1}) had an impact on the growth of the content of total nitrogen compared to the smallest dose (1.0 t ha^{-1}).

In our experiment, MBM applied to soil significantly affected the content of copper in soil only in 2009. The lowest dose of MBM increased the amount of available Cu in soil by 10% compared to the 'no fertilization' site. The application of higher doses of MBM (1.5-2.5 t ha^{-1}) resulted in a significant decrease in the copper content, on average namely by 10% compared to the 'no fertilization' treatment and by 6.7% compared to the 'mineral fertilization' site. This may have been caused by a stronger effect of the residual copper on yield achieved at these sites (Stępień 2011). According to Rutkowska et al. (2014), manure reduced the concentration of Cu in the soil solution compared to soil nourished with mineral fertilizers. Sienkiewicz et al. (2009) showed a 1.7-fold increase in the content of available copper forms in soil regularly fertilized with manure.

Behera et al. (2011) claim that an increase in the soil content of zinc is caused by organic matter because zinc tends to form unstable organic-mineral complexes. The content of zinc determined by the above authors in 2008 and 2009 was unaffected by the fertilization systems. The significant effect of the high doses of MBM applied in 2007 was statistically validated. The application of MBM at 2.0 and 2.5 t ha^{-1} decreased the zinc content in soil by 19.9% and 17.8%, respectively, compared to the 'no fertilization' site. The amount of available Mn and Fe in the soil did not change under the influence of the different fertilization patterns. According to Yuan (2009), an increase in the organic matter applied as a biosolid resulted in higher concentrations and activity of Cu, Zn and Mn. Although nitrogen in MBM occurs mainly in proteins (Delin, Engstrom 2010), according to Jeng et al. (2004) it is immediately available to crops. Eghball et al. (2002) claim that the availability of Zn, Mn and Cu in manure is less than 40%. According to Wołoszyk et al. (2009), the uptake of different micronutrients from sludge and straw by test crops was: Mn – 58.2%, Zn – 5.54%, and Cu – 3.03%.

Although the chemical content of MBM implicates its good fertilizer value, the study did not demonstrate a clearly defined impact of the increased MBM doses on the content of the analysed elements in the soil. This may have been the consequence of the increase of bioavailable nitrogen forms, which constitute part of the sorption complex (Jeng et al. 2004). Their bioavailability may also be subject to mutual relationships among elements, which may act antagonistically (Fe and Mn, Ca and Zn).

The highest content of Cu in the current experiment was found after the application of MBM at 2.5 t ha^{-1} in winter wheat grain – 2007 (3.41 mg kg^{-1}), at 1.5 t ha^{-1} in winter oilseed rape seeds – 2008 (1.94 mg kg^{-1}) and at 1.0 t ha^{-1} in spring wheat grain – 2009 (3.01 mg kg^{-1}) – Table 5.

In 2007, all the variants of fertilization with MBM increased the copper content in winter wheat grain compared to the control sites (no fertilizers and NPK). The application of MBM at 2.5 t ha^{-1} increased the content of copper by 53.6% compared to the 'no fertilization' site and by 39.2% compared to the site with NPK fertilization. Fertilization with MBM at 1.5 t ha^{-1} resulted in a significant increase in the copper content by 94.0% in seeds of oilssed rape (2008) compared to mineral fertilization. MBM at 1.0 t ha^{-1} increased the content of copper by 22.4% and 27.0% in the cultivation of spring wheat (2009) (compared to the site without fertilization and the one fertilized with NPK).

The fertilization variants tested in our experiment raised, albeit not always significantly, the amount of zinc in the plant material. A particularly

Table 5

Micronutrient content in wheat (spring and winter) grain and in winter oilseed rape seeds (mg kg^{-1} of DM)

Treatments	Cu	Zn	Mn	Fe
2007 (winter wheat)				
Without fertilization	$2.22^{c} \pm 0.05$	$20.1^{c} \pm 0.50$	$19.9^{d} \pm 1.41$	$21.3^{b} \pm 1.91$
NPK	$2.45^{c} \pm 0.16$	$28.8^{ab} \pm 0.92$	$27.8^{ab} \pm 1.20$	$30.1^{a} \pm 1.27$
MBM 1.0 t ha^{-1}	$3.12^{ab} \pm 0.09$	$26.5^{b} \pm 1.13$	$22.0^{cd} \pm 1.41$	$25.4^{ab} \pm 0.78$
MBM 1.5 t ha^{-1}	$2.95^{b} \pm 0.24$	$28.9^{ab} \pm 1.56$	$21.2^{cd} \pm 2.19$	$26.5^{ab} \pm 2.69$
MBM 2.0 t ha^{-1}	$3.33^{ab} \pm 0.17$	$31.1^{a} \pm 1.41$	$25.0^{bc} \pm 0.57$	$25.7^{ab} \pm 5.94$
MBM 2.5 t ha^{-1}	$3.41^{a} \pm 0.21$	$31.2^{a} \pm 3.19$	$28.9^{a} \pm 1.49$	$28.7^{a} \pm 1.69$
2008 (winter rape)				
Without fertilization	$1.81^{a} \pm 0.16$	$24.5^{ab} \pm 0.35$	$30.4^{a} \pm 0.85$	$63.0^{a} \pm 4.24$
NPK	$1.00^{b} \pm 0.35$	$22.2^{b} \pm 1.13$	$29.6^{a} \pm 5.09$	$62.5^{a} \pm 4.95$
MBM 1.0 t ha^{-1}	$1.32^{ab} \pm 0.07$	$26.4^{a} \pm 0.64$	$29.1^{a} \pm 2.97$	$65.0^{a} \pm 5.66$
MBM 1.5 t ha^{-1}	$1.94^{a} \pm 0.22$	$24.8^{a} \pm 1.07$	$31.2^{a} \pm 0.07$	$62.3^{a} \pm 0.28$
MBM 2.0 t ha^{-1}	$1.64^{ab} \pm 0.57$	$25.2^{a} \pm 1.34$	$29.5^{a} \pm 3.89$	$66.3^{a} \pm 1.63$
MBM 2.5 t ha^{-1}	$1.36^{ab} \pm 0.20$	$24.7^{a} \pm 0.78$	$29.6^{a} \pm 0.64$	$65.8^{a} \pm 3.39$
2009 (spring wheat)				
Without fertilization	$2.46^{c} \pm 0.16$	$24.8^{bc} \pm 0.35$	$22.1^{abc} \pm 0.99$	$24.3^{c} \pm 1.56$
NPK	$2.37^{c} \pm 0.09$	$26.9^{abcd} \pm 0.71$	$26.1^{a} \pm 0.92$	$31.9^{a} \pm 2.62$
MBM 1.0 t ha^{-1}	$3.01^{a} \pm 0.33$	$27.8^{abcd} \pm 0.21$	$24.4^{ab} \pm 1.06$	$31.5^{ab} \pm 3.23$
MBM 1.5 t ha^{-1}	$2.78^{bc} \pm 0.31$	$30.4^{ab} \pm 0.38$	$23.3^{abc} \pm 2.97$	$32.4^{a} \pm 1.50$
MBM 2.0 t ha^{-1}	$2.79^{bc} \pm 0.08$	$29.0^{abcd} \pm 0.21$	$22.6^{abc} \pm 3.11$	$28.7^{bc} \pm 3.54$
MBM 2.5 t ha^{-1}	$2.36^{c} \pm 0.86$	$29.3^{abc} \pm 2.12$	$23.7^{ab} \pm 2.05$	$29.6^{ab} \pm 1.70$

NPK - mineral fertilization, MBM – meat and bone meal
a, *b*, *c*, … values with the same letter are not significantly different according to the Duncan's test ($p \leq 0.05$), ± SD (standard deviation)

beneficial effect of the higher doses of MBM (2.0 and 2.5 t ha^{-1}) was found for winter wheat grain (average increase by 55.0% compared to the 'no fertilization' site). The application of MBM increased the Zn content in seeds of winter oilseed rape (2008) by an average 13.8% compared to the 'mineral fertilization' site. The dose of 1.5 t ha^{-1} and 2.5 t ha^{-1} increased the content of zinc in grain of spring wheat by 22.6% and 18.1%, respectively, compared to the 'no fertilization' site.

In general, the application of MBM resulted in an increased content of Mn in winter wheat grain. The higher doses of MBM (2.0 and 2.5 t ha^{-1}) increased the manganese content in winter wheat grain by 25.6% and 45.2%, respectively, compared to the 'no fertilization' site.

The dose of 2.5 t ha^{-1} MBM increased the content of Fe in grain of winter wheat in 2007. Same as NPK fertilization, the application of MBM at 2.5 t ha^{-1} increased the content of this nutrient in grain (by 34.7% and 41.3%, respectively) compared to the 'no fertilization' site. MBM supplied at 1.0, 1.5 or 2.5 t ha^{-1} significantly increased the content of iron in spring wheat grain (2009) compared to the 'no fertilization' variant. The highest concentration of Fe (32.4 mg kg^{-1}) was found following the application of MBM at 1.5 t ha^{-1}.

According to Gondek (2012), the content of Zn in wheat grain in the third year of manure, sludge or NPK application was found to have increased by 42.5%, 28.7% and 12.7%, respectively, compared to the first year of the experiment. According to the cited author, the application of manure increased the content of Cu, while the application of compost increased the content of Mn in grain.

An increase in the content of micronutrients in soil is not always accompanied by a subsequent increase in their concentrations in crops (Wojtkowiak et al. 2014). This was confirmed by a regression analysis on the composition of soil and grain and seeds of oilseed rape (Figures 1-2). Our analysis of the relationships between the micronutrients has shown a significant decrease in the zinc content in winter wheat grain (2007) and seeds of oilseed rape 2008) parallel to the increased in the soil content of this nutrient. The determination coefficient for the relationship between the content of zinc in soil and in

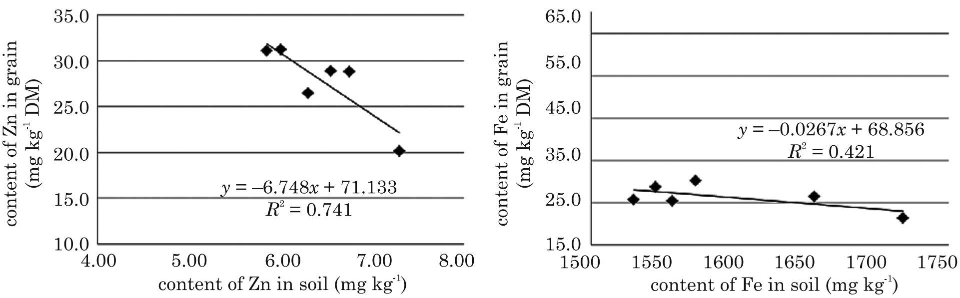

Fig. 1. Relationships between the micronutrient content in winter wheat grain and in soil in 2007

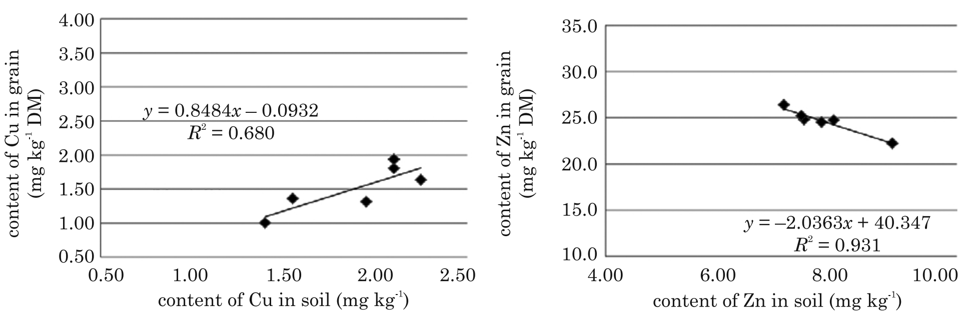

Fig. 2. Relationships between the micronutrient content in seeds of winter rape and in soil in 2008

winter oilseed rape was closest to the linear correlation coefficient ($R^2 = 0.931$). A reverse relationship, i.e. an increase in the zinc content in triticale grain versus its increasing content in soil, was demonstrated by Wojtkowiak et al. (2014). It was shown that the content of iron in grain of winter wheat in 2007 decreased significantly alongisde its increasing content in soil ($R^2 = 0.421$). The content of copper in seeds of winter oilseed rape in 2008 was found to increase with its increasing content in soil. The absence of a clear impact on the metal content in wheat grains and oilseed rape seeds may have been caused by the lack of influence of the increasing doses of MBM on the nutrient content in the soil.

CONCLUSIONS

1. The experiment did not show any effect of the increasing doses of meat and bone meal (MBM) on the concentrations of micronutrients in soil. The application of higher MBM doses was followed by a considerable decrease in the content of Cu in 2009 (in response to 1.5, 2.0 t MBM ha^{-1}) and of Zn in 2007 (2.0 and 2.5 t ha^{-1}).

2. Fertilization with MBM at 2.5 t ha^{-1} improved the quality of grain of winter wheat by increasing the content of Cu, Fe, Mn and Zn.

3. Our analysis of the micronutrient content revealed a significant decrease in Zn and Fe in winter wheat grain and Zn in winter oilseed rape as the content of these nutrients in the soil increased. Regarding the relationship between the Zn content in soil and in winter rape seeds, the coefficient of determination was the closest to the coefficient of linear correlation. It was only in 2008 that an increase in the Cu content in winter rape found following an increase in the soil content of this micronutrient.

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