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CHANGES IN THE CHEMICAL PROPERTIES OF GROUNDWATER IN SOILS UNDER MEAT AND BONE MEAL, NATURAL AND MINERAL FERTILIZATION REGIMES

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Abstract

The objective of this study was to evaluate the effect of different doses of meat and bone meal (MBM) applied as organic fertilizer on the quality of groundwater in arable fields. The effect of meat and bone meal fertilizer applied at rates of 1.0, 1.5, 2.0 and 2.5 t ha^{-1} was compared with no fertilization, mineral fertilization, and manure fertilization (10 t ha^{-1}). Groundwater samples for chemical analyses were collected every month during the growing season using piezometers installed in the experimental plots. Groundwater samples were analyzed to determine the concentrations of mineral nitrogen – NO_3^-, NO_2^- and NH_4^+, total phosphorus, phosphate and potassium. The application of meat and bone meal at the rate of 1.0 to 2.0 t ha^{-1} with supplemental potassium fertilization does not lead to higher contamination of groundwater than mineral (NPK) fertilization. The use of meat and bone meal fertilizers at a rate of 2.5 t ha^{-1} significantly increased mineral nitrogen and phosphate concentrations in groundwater samples. The results of our analyses suggest that meat and bone meal can be successfully used at a rate of 2.0 t ha^{-1} to fertilize crops grown in a five-year crop rotation sequence on lessive soils. The application of higher doses of meat and bone meal intensifies the flow of biogenic elements into groundwater.

Key words: groundwater contamination, meat and bone meal, organic waste

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1. Introduction

The conservation or enhancement of the soil organic contents is generally acknowledged as an important objective for each system belonging to the sustainable agriculture. Loss of the organic substances has a negative effect on the soil chemical, physical and biological properties (Zaharia et al., 2010). Soil fertilizers containing meat and bone meal are a rich source of nutrients for crop plants (Konopka et al., 2012; Stępień and Szymczyk, 2009; Stępień and Wojtkowiak, 2013). As of 1 November 2003, the by-products of the meat processing industry, including meat and bone meal, may not be added to feed stuff administered to animals whose meat is intended for human consumption. This legal ban has increased the availability of meat and bone meal as soil fertilizers. At present, meat and bone meal is used chiefly as fuel in cement plants and brick kilns (Ayllón et al., 2006; Beck et al., 2004; Coutand et al., 2008; Cummins et al., 2006; Deydier et al., 2005, 2007). According to Gulyurtulu et al. (2005), other meal processing options do not guarantee sanitary safety, and burning is the only method that fully eliminates BSE (*Bovine Spongiform Encephalopathy*) pathogens from meat and bone meal. Meal burning is controversial owing to economic factors as well as environmental considerations, including the risk of toxic gas release

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into ambient air. The rendering industry is currently searching for new methods supporting the use of meat and bone meal as organic fertilizers in farming (Jeng et al., 2004). Meat and bone meal is an alternative source of organic matter that is supplied to soil with other fertilizers, such as manure (Konopka et al., 2012). Meat and bone meal is also a rich source of available forms of nitrogen and phosphorus (Jeng et al., 2006; Tenuta and Lazarovits, 2003; Ylivainio et al., 2008). The use of MBM as a source of nitrogen and phosphorus and its beneficial effect on the yield and biological quality has been confirmed by the findings of studies by Chen et al. (2011), Konopka et al. (2012), Stępień and Wojtkowiak (2013).

Organic farming of plants involves using organic fertilizers. The most commonly applied organic fertilizers include manure and compost. They provide organic matter to the soil, which is transformed into humus by earthworms and microorganisms (Choudhary et al., 1996; Winter and Davis, 2006). Moreover, they contain easily available forms of nitrogen, phosphorus (P) and potassium (K) in amounts necessary for development and high yield of plants, and they also inhibit weed germination (Choudhary et al., 1996; Prassad et al., 2002). Organic fertilizers increase soil water potential and the amount of water available to plants. Thereby, they have a positive effect on the absorption of minerals during the periods of soil water shortage, which results in increased yield, thousand kernel weight, and protein concentration in grain (Liu et al., 2004; Yang et al., 2004). The concentrations of biogenic elements in groundwater are correlated with the quantity of minerals leached out of the soil. The rate of mineral flow is determined by the type of soil use, the granulometric composition and soil compaction, cultivation regime (mainly fertilization type and rate), availability of drainage systems, toxic air pollution and atmospheric deposition (Koc et al., 2007; Szymczyk, 2010a; Vagstad et al., 2000). According to various authors, increased use of agricultural chemicals is the main source of surface water and groundwater pollution (Koc et al., 2007; Szymczyk, 2010a). There are concerns about groundwater contamination with N and P from fertilizers and other anthropogenic wastes (Blum et al., 2013).

The objective of this study was to evaluate the effect of different doses of meat and bone meal on the concentrations of biogenic elements in groundwater and groundwater contamination in comparison with mineral (NPK) and manure fertilization.

2. Materials and methods

2.1. Site and experimental set-up

The effect of different doses of meat and bone meal applied as organic fertilizer in medium-heavy lessive soils on the chemical properties of groundwater was studied in 2007-2009 at the Production and Experimental Station in Bałcyny (53º36’ N; 19º51’E), Poland. The study was carried out in an experimental field of 0.25 ha in a region with lightly undulating topography (with a slope of up to 3%). Soils were classified based on the Polish Soil Taxonomy System and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). A field experiment was set up on a proper lessive soil (Ap-Eet-Bt) in a randomized block design in 4 repetitions. The surface layer of the soil profile (Ap) was a heavy loamy sand, and the E-horizon consisted of clay underlain by light loam in the illuvial horizon (Bt). The experimental area comprised class IIIa soil (arable soil of good quality). The lessive soil was slightly acidic (in KCl solution with a pH = 6.5) with a total nitrogen content of 0.91%. The following concentrations of plant-available macronutrients were determined in the studied soil: P – 9.27 mg (100 g)$^{-1}$; K – 17.8 mg (100 g)$^{-1}$; Mg – 5.72 mg (100 g)$^{-1}$ and Ca – 56.0 mg (100 g)$^{-1}$. The long-term field experiment was performed in a four-course crop rotation sequence. In the successive years of the study, the field was sown with winter wheat, winter rape and spring wheat. The following fertilization treatments were applied: 1) no fertilization, 2) NPK – mineral fertilization at the rate of: N – 90 kg ha^{-1}, P – 70 kg ha^{-1}, K – 83.1 kg ha^{-1}, 3) farmyard manure (FYM) fertilization (10 t ha^{-1} per annum), 4) MBM-1.0 – meat and bone meal fertilization at a rate of 1.0 t ha^{-1}, 5) MBM-1.5 – meat and bone meal fertilization at a rate of 1.5 t ha^{-1}, 6) MBM-2.0 – meat and bone meal fertilization at a rate of 2.0 t ha^{-1}, 7) MBM-2.5 – meat and bone meal fertilization at a rate of 2.5 t ha^{-1}. A detailed specification of the nutrients supplied with the fertilizers is presented in Table 1.

On the experimental object fertilized with mineral fertilizer (NPK), winter rape, spring and winter wheat were fertilized with nitrogen at 60 kg ha^{-1} before seeding and at 30 kg ha^{-1} at BBCH 31-32. Phosphorus fertilizers were applied before seeding at 31 kg ha^{-1} as triple superphosphate (46%) and fertilization with potassium was used at 83.1 kg ha^{-1} as 60% potassium salt. Farmyard manure (FYM) were introduced annually at 10 t ha^{-1} in the pre-seeding system of summer-autumn (winter rape and wheat) or spring (spring wheat) cultivations.

Seeding, cultivation procedures and the harvesting of winter wheat, winter rape and spring wheat were carried out in accordance with the agricultural engineering requirements specific for a given plant species. Weeds were eradicated only by mechanical means. The elimination of diseases and pests was not performed.

2.2. Meal meat bone (MBM)

The MBM used in the study was in the form of powder and classified as category 3, which comprises animal by-products derived from the manufacture of products intended for human consumption and it was purchased from the Animal By-Products Disposal Plant SARIA Poland. MBM contained, on average, 95.5% DM, 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. Meat bone meal

(MBM) was applied before seeding. The maximum doses of meat and bone meal were within the norm stipulated by the Regulation of the Ministry of Agriculture and Rural Development of 7 December 2004 (as amended) on veterinary requirements for soil conditioners. Due to very low potassium concentrations in meat and bone meal (0.3-0.6% K), potassium was applied additionally at 83.1 kg K ha^{-1} in the MBM treatments.

2.3. Sampling, measurements, and analyses

Groundwater samples for chemical analyses were collected every month between March and October (spring, summer, fall) using piezometers installed in the experimental plots. Samples were not collected in the winter due to low groundwater levels. Groundwater samples were analyzed to determine the concentrations of: nitrate (NO_3^-) – by colorimetry with phenol-disulfonic acid; nitrite (NO_2^-) – by colorimetry with sulfanilic acid; ammonia – by colorimetry with Nessler's reagent; total phosphorus (P_{total}) and phosphate (PO_4^{3-})– after mineralization with ammonia molybdate and tin (II) chloride as the reducing agent. Total concentration of mineral nitrogen was expressed as the sum of NO_3^-, NO_2^- and NH_4^+. The concentration of total phosphorus in mg dm^{-3} P and phosphate phosphorus is expressed in mg dm^{-3} PO_4^{3-}. The ranges of determinability for individual compounds: NO_3^- – 0.02 – 4.50 mg dm^{-3}; NO_2^- – 0.001 – 4.300 mg dm^{-3}; NH_4^+ – 0.001 – 0.050 mg dm^{-3}; PO_4^{3-} – 0.05 – 1.50 mg dm^{-3}; total P – 0.05 – 1.50 mg dm^{-3}.

2.4. Weather conditions

In 2007-2009, air temperature during the growing season (March to October) was 0.6 to 1.1ºC higher on average in comparison with the multi-annual average for 1961-2000 (Table 2). The warmest growing season was noted in 2007 (12.5ºC on average) when average temperatures for March, May and June were higher than those reported during the two subsequent years of the experiment. In comparison with other years of the study and the long-term average, the growing season of 2007 was also characterized by the lowest temperature variability (*V* = 41%).

Precipitation levels differed between the growing seasons of 2007-2009, and variations were also noted in reference to the multi-annual average. The growing season of 2007 was characterized by the highest level of precipitation (123% of the long-term average), whereas 2008 - the driest year of the study (93% of the long-term average) - was classified as average. The highest variability in total monthly precipitation (*V* = 73%) was reported in the growing season of 2009, but it did not differ significantly (3%) from the multi-annual average. In comparison with the long-term average, deficient precipitation was noted in April, August and September, and surplus precipitation in May and June.

Table 1. Doses of nutrients in kg ha^{-1} with the yearly fertilizer application

Content of mineral compound [kg ha^{-1}]	***System of fertilization***			
	No fertilization	***Mineral fertilization (NPK)***	***Farmyard manure (FYM)***	***Meat and bone meal* (MBM-1.0)***
N	-	90.0	51.0	66.5
P	-	31.0	12.1	39.8
K*	-	83.1	49.0	4.1+83.1**
Mg	-	-	8.0	2.0
Ca	-	-	34.0	19.0
Dose of fertilizer			10 t ha^{-1}	1.0 t 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}*

*** Treatments fertilized with meat and bone meal were additionally supplied with 83.1 kg K ha^{-1}*

Table 2. Weather conditions in Bałcyny in 2007-2009 and the multi-annual average of 1961-2000

Years	***Months***									
	III	***IV***	***V***	***VI***	***VII***	***VIII***	***IX***	***X***	***III - X***	
Temperature (ºC)									Average	*V* (%)
2007	5.4	7.3	13.7	17.5	17.5	18.2	12.6	7.4	12.5	41
2008	2.9	7.8	12.3	16.6	18.3	17.8	11.8	8.7	12.0	45
2009	1.9	9.7	12.2	14.7	18.9	18.5	14.7	5.9	12.1	49
2007-2009	3.4	8.3	12.7	16.3	18.2	18.2	13.0	7.3	12.2	45
1961–2000	1.4	7.0	12.5	15.8	17.2	16.8	12.6	8.1	11.4	49
Precipitation (mm)									Sum	*V* (%)
2007	27.9	26.8	79.7	60.8	176.5	81.0	65.4	48.9	567.0	67
2008	47.1	33.8	48.4	27.8	47.0	103.1	17.0	104.6	428.8	61
2009	68.0	3.7	89.6	133.1	82.2	25.7	15.6	58.5	476.4	73
2007-2009	47.7	21.4	72.6	73.9	101.9	69.9	32.7	70.7	490.7	42
1961–2000	29.0	35.0	58.0	70.0	82.0	75.0	59.0	54.0	462.0	32

V – coefficient of variation

2.5. Statistical analyses

The results were processed statistically using the Statistica 9PL application. Coefficients of linear correlation (Pearson's r - at $\alpha = 0.05$) were calculated, the Shapiro-Wilk normality test was performed (at $\alpha = 0.05$), and the Kruskal-Wallis test was carried out to determine the homogeneity of variance.

3. Results and discussion

Nutrient flow dynamics in the soil and nutrient leaching out of the solid phase are determined by the granulometric soil composition, the abundance of macro-elements and micro-elements, and weather conditions. Those factors affect the flow of biogenic elements which are accumulated in the soil adsorption complex; undergo phytosorption or migrate to groundwater and are evacuated to surface waters via drainage systems (Koc et al., 2007; Szymczyk, 2010a; Vagstad et al., 2000).

Many researchers (Chaves et al., 2005; Jeng et al., 2006; Jeng and Vagstad, 2009) have reported that, through mineralization of MBM, N is released to the soil and it usually becomes available to plants during the first year when MBM is used. However, being affected by numerous factors, the process of mineralization of organic matter is highly unpredictable. Therefore, the amount and timing of the application of such waste should be considered carefully in order to avoid loss of NO_3-N and to optimize N use. Jeng and Vagstad (2009) go so far as to recommend that the fertilizer should not be used in early spring or in late summer because of the possibility of N loss to the environment.

The concentrations of the analyzed forms of mineral nitrogen (NO_2^-, NO_3^-, NH_4^+) varied subject to fertilizer type and application rates (Table 3). The noted differences can be attributed to the mineralization of organic nitrogen compounds contained in meat and bone meal. Due to the high rate of release of NO_3^- and NH_4^+, excess compounds that were not used by crop plants were leached into the groundwater.

NO_3^- is the predominant form of mineral nitrogen in groundwater (Szymczyk, 2010a) and surface water which is evacuated via drainage systems (Vagstad et al., 2000). In the analyzed groundwater samples, NO_3^- accounted for 93 to 99% of the mineral nitrogen. The highest variations in the concentrations of NO_3^- and total mineral nitrogen were reported in groundwater samples from soils fertilized with meat and bone meal at the rate of 2.0 t ha^{-1} (1.43 to 198.46 mg dm^{-3}) and with NPK (1,33 to 194.92 mg dm^{-3}). In the above treatments and in plots fertilized with meal at the rate of 2.5 t ha^{-1}, nitrogen levels in groundwater were significantly higher in comparison with the other sites (Fig. 1). The highest variations in NO_2^- concentrations (0.020 to 0.821 mg dm^{-3}) were observed in the plot with meat and bone meal applied at a rate of 2.5 t ha^{-1}.

The lowest concentrations of NH_4^+ (0.015 mg dm^{-3}) were noted in the unfertilized treatment, and the highest (0.966 mg dm^{-3}) in the plot supplied with meat and bone meal at a rate of 2.5 t ha^{-1} with significantly higher values than in the other treatments.

Table 3. Average annual concentrations of mineral nitrogen compounds in the groundwater, subject to the soil fertilization regime (mg dm^{-3})

Year	***System of fertilization***						
	No fertilization	***NPK***	***FYM***	***MBM-1.0***	***MBM-1.5***	***MBM-2.0***	***MBM-2.5***
Total N							
2007	14.97 a	32.14 c	24.45 b	16.47 a	20.41 b	20.72 b	30.25 c
2008	8.29 ab	12.43 b	10.43 b	13.93 c	5.96a	14.25 c	12.79 bc
2009	4.22 a	17.59 c	12.36 b	7.06 ab	7.50 ab	15.93 c	20.30 c
Average	9.16 a	20.72 b	15.75 ab	12.49 ab	11.29 a	16.96 b	21.11 b
NO_3^-							
2007	66.77 a	142.17 c	108.17 b	72.89 ab	89.93 b	91.62 b	132.01c
2008	36.50 a	54.93 b	61.58 ab	61.58 c	26.23 a	62.91 c	54.08 b
2009	18.38 a	77.58 c	30.83 b	30.83 a	32.90 a	70.35 b	88.92 c
Average	40.22 a	91.56 b	55.10 ab	55.10 ab	49.68 a	74.96 b	91.67 b
NO_2^-							
2007	0.099 b	0.083 b	0.048 ab	0.018 a	0.063 ab	0.037 ab	0.365c
2008	0.045 b	0.021 a	0.055 b	0.059 b	0.020 a	0.058 b	0.805 c
2009	0.019 a	0.032 ab	0.066 b	0.042 ab	0.016 a	0.022 a	0.040 b
Average	0.054 a	0.045 a	0.056 a	0.040 a	0.033 a	0.039 a	0.403 b
NH_4^+							
2007	0.120 b	0.028 a	0.028a	0.017 a	0.112 b	0.038 a	0.438 c
2008	0.047 b	0.034 ab	0.024 a	0.015 a	0.041 b	0.039 b	0.431 c
2009	0.082 ab	0.092 ab	0.247 b	0.116 ab	0.094 ab	0.049 a	0.283 c
Average	0.083 a	0.052 a	0.099 a	0.049 a	0.082 a	0.042 a	0.384 b

a,b …the values denoted with the same letter constitute a homogenous group and are not statistically significantly differentiated according to the Kruskal-Wallis test ($\alpha = 0.05$)

No significant differences in the concentrations of NO_2^- and NH_4^+ were found between the unfertilized control and the fertilized experimental plots, including the treatment fertilized with meat and bone meal at the rate of 2.0 t ha^{-1}. The above suggests that a meat and bone meal dose up to 2.0 t ha^{-1} does not contribute to groundwater contamination with NO_3^- or NH_4^+. The highest concentrations of total mineral nitrogen (21.11 mg dm^{-3} on average) were reported in the groundwater of the treatments with meat and bone meal applied at a rate of 2.5 t ha^{-1}, and the lowest (9.16 mg dm^{-3} on average) in the unfertilized plot. In soils amended with mineral fertilizers (NPK), the total mineral nitrogen level in the groundwater samples reached 20.72 mg dm^{-3}, which was two-fold higher than the control and experimental treatments fertilized with meat and bone meal at 1.0 and 1.5 t ha^{-1}.

The average concentrations of nitrogen compounds noted in the experimental period indicate that the application of meat and bone meal at the rate of 2.5 t ha^{-1} increases NO_2^- concentrations in groundwater 7- to 12-fold and NH_4^+ concentrations 4- to 8-fold. The reported high variations in the studied forms of nitrogen in the groundwater samples were strongly influenced by the volume and distribution of precipitation in the growing season. The above observation is validated by the highest concentrations of NO_3^- and mineral nitrogen in all treatments in the wettest year of the study (2007). Such close correlations between precipitation and the amount of total mineral nitrogen and NO_3^- in the groundwater were not reported in the successive years which were less diverse in precipitation levels. It could have been related to organic nitrogen delivered to soil in the amount that overwhelmed the capacity for efficient microbial degradation, especially under unfavourable humidity. As a result, it could have significantly prolonged the first stage of nitrification and caused washing out of NO_3^- to ground waters after intensive precipitation (Szymczyk 2010b).

The concentrations of NO_2^- and NH_4^+ in the groundwater varied widely between experimental treatments, showing a weaker correlation with annual precipitation totals. The calculated correlation coefficients illustrate the varied effect of precipitation on groundwater contamination caused by mineral nitrogen compounds (Table 4). The above data indicate that NO_2^- and NH_4^+ concentrations in groundwater increased significantly with increasing precipitation only in selected treatments, in particular in unfertilized plots and the treatments amended with manure.

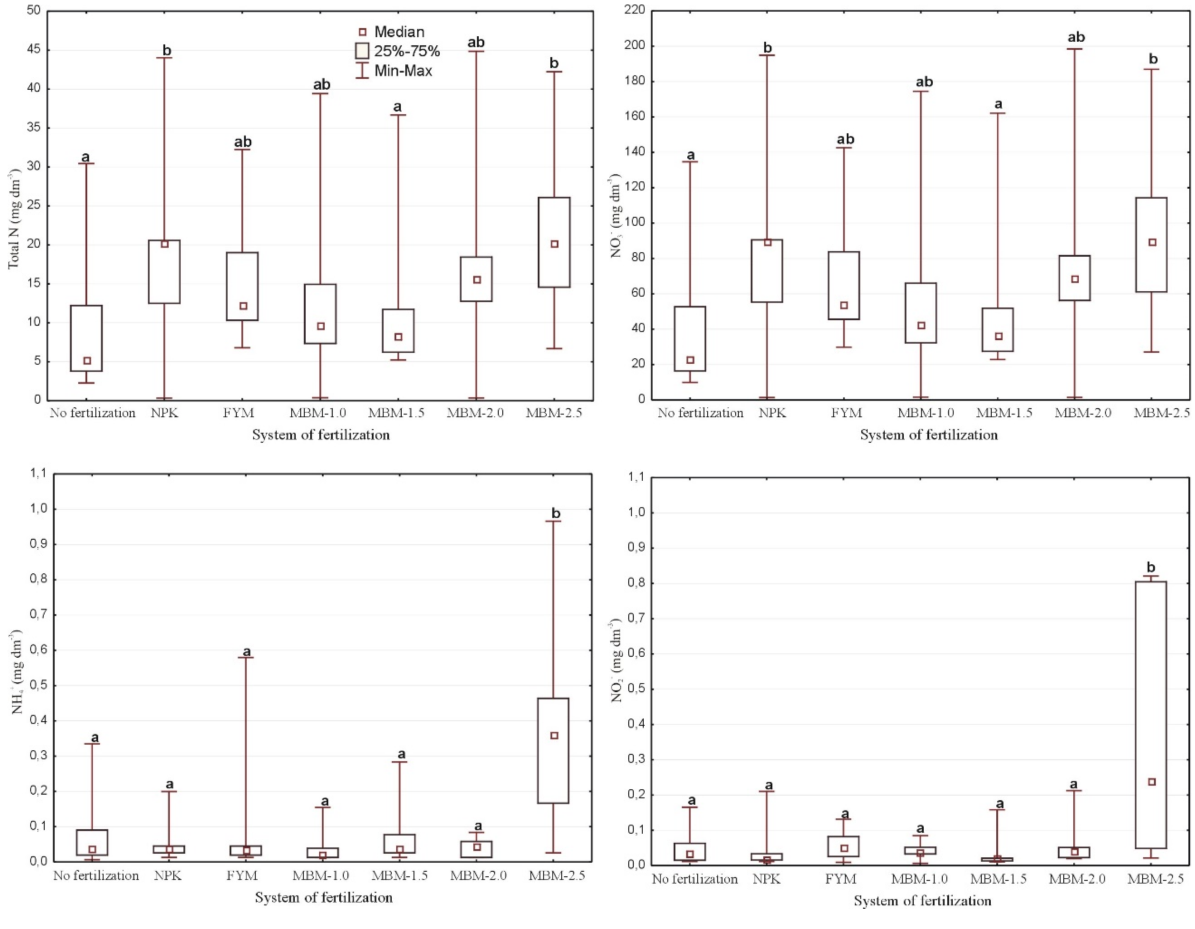

Fig. 1. The effect of soil fertilization regime on variations of mineral nitrogen concentrations (mg dm^{-3}) in the groundwater (a,b …the values denoted with the same letter constitute a homogenous group and are not statistically significantly differentiated according to the Kruskal-Wallis test ($\alpha = 0.05$))

Table 4. Correlations between precipitation and nitrogen, phosphorus and potassium concentrations in the groundwater (N = 63, $\alpha = 0.05$)

Compounds	*No fertilization*	*NPK*	*FYM*	*MBM-1.0*	*MBM-1.5*	*MBM-2.0*	*MBM-2.5*
Total N	–	–	–	–	–	–	–
NO_3^-	–	–	–	–	–	–	–
NO_2^-	0.60*	–	0.60*	–	–	0.71*	0.60*
NH_4^-	0.90*	–	0.90*	–	0.96*	–	–
Total P	–	–	0.72*	–	–	–	–
PO_4^{3-}	0.64*	–	0.64*	–	–	–	0.64*
K	0.68*	–	0.68*	0.83*	–	–	0.68*

**essential correlations; –no essential relation*

Table 5. Average seasonal concentrations of mineral nitrogen compounds in groundwater, subject to the soil fertilization regime (mg dm^{-3})

Season	*System of fertilization*						
	No fertilization	*NPK*	*FYM*	*MBM-1.0*	*MBM-1.5*	*MBM-2.0*	*MBM-2.5*
			Total N				
Spring	12.70 a	25.74 b	21.16 b	18.80 ab	17.11 ab	23.65 b	25.34 b
Summer	7.80 a	18.70 b	11.91 ab	9.62 a	7.95 a	15.80 ab	18.38 b
Autumn	6.98 a	17.73 bc	14.18 b	9.04 a	8.81 a	11.44 ab	19.62 c
			NO_3^-				
Spring	55.95 a	113.54 b	93.47 b	83.15 a	75.53 ab	104.55 b	110.62 b
Summer	33.89 a	82.71 c	51.92 ab	42.35 a	34.55 a	69.73 b	79.34 c
Autumn	30.83 a	78.46 b	62.68 ab	39.78 a	38.94 a	50.59 ab	85.10 b
			NO_2^-				
Spring	0.072 ab	0.102 b	0.039 a	0.039 a	0.069 ab	0.036 a	0.292 c
Summer	0.079 b	0.020 a	0.089 b	0.036 a	0.016 a	0.036 a	0.552 c
Autumn	0.013 a	0.016 a	0.039 b	0.043 b	0.013 b	0.043 b	0.365 c
			NH_4^+				
Spring	0.058 ab	0.100 b	0.062 ab	0.022 a	0.043 ab	0.055 ab	0.367 c
Summer	0.171 b	0.030 a	0.213 b	0.067 a	0.180 b	0.057 a	0.399 c
Autumn	0.019 a	0.023 a	0.023 a	0.061 b	0.023 a	0.013 a	0.386 c

a,b …the values denoted with the same letter constitute a homogenous group and are not statistically significantly differentiated according to the Kruskal-Wallis test ($\alpha = 0.05$)

Precipitation volumes and groundwater contamination with mineral nitrogen compounds were not correlated in any of the experimental years. A clear relationship between precipitation levels in 2007-2009 and concentrations of total mineral nitrogen and NO_3^- in groundwater samples was not observed in any of the experimental treatments. The above could be attributed to the seasonal variability in precipitation patterns over the experimental period as well as the crop rotation in successive years of the experiment. Crop plants have varied nitrogen requirements, and vegetation cover limits water and nutrient migration into the soil profile. This observation is supported by the fact that the poorest plant growth and the lowest yield were noted in the unfertilized treatment and plots fertilized with manure only. Our results also indicate that discontinuation of soil fertilization does not prevent the contamination of groundwater with biogenic elements. The opposite was observed – nutrient leaching rates from the soil were higher in wet years.

The highest average concentrations of total mineral nitrogen, from 12.70 mg dm^{-3} in the control treatment to 25.74 mg dm^{-3} in the NPK-fertilized treatment, were observed in groundwater samples collected in the spring, whereas the lowest levels of mineral nitrogen were noted in the control treatment in the fall (6.98 mg dm^{-3} on average) and, in the majority of cases, also in the summer (Table 5). Particularly high NO_3^- concentrations were reported in the spring in treatments fertilized with NPK (25.74 mg dm^{-3}) and meat and bone meal at the rate of 2.5 t ha^{-1} (25.34 mg dm^{-3}). The above values were noted before and at the beginning of the growing season when bio-sorption of nitrogen is limited. The results of statistical calculations indicate that mineral nitrogen concentrations in the above treatments were significantly higher than in the other plots. In the summer, a substantial portion of nitrogen released during the mineralization of organic matter which is supplied with meat and bone meal is most readily absorbed by crop plants. Evaporation generally exceeds precipitation in summer, thus significantly lowering groundwater levels, which may limit the migration of mineral nitrogen into the soil profile (Szymczyk, 2010a). All of the analyzed nitrogen forms were most readily leached in the treatment fertilized with meat and bone meal at the rate of 2.5 t ha^{-1}.

Subject to the fertilization regime and weather conditions, total phosphorus concentrations in groundwater ranged from 0.06 mg dm^{-3}, including 0.09 mg dm^{-3} PO_4^{3-} in the unfertilized treatment, to 1.14 mg dm^{-3} total phosphorus, including 1.36 mg dm^{-}

^{3} PO_4^{3-} (Fig. 2). All of the tested fertilizers increased phosphorus concentrations in groundwater. In comparison with the control, a significant increase in total phosphorus and phosphate levels was noted only in the treatment fertilized with the highest dose of meat and bone meal.

The introduction of a varied fertilization regime increased the average phosphorus and phosphate concentrations in groundwater by 86 and 83%, respectively (Table 6). The highest increase was noted in treatments fertilized with meat and bone meal which supplied large amounts of phosphorus – an average of 193 kg ha^{-1} NPK per annum, including 60 kg ha^{-1} of phosphorus. Treatments where meat and bone meal was applied at the highest rate (2.5 t ha^{-1}) received nearly 100 kg ha^{-1} of phosphorus (Table 1). Phosphorus supplied with meat and bone meal was relatively available, and it was organically bound. In comparison with nitrogen, phosphorus is generally less likely to migrate into the soil profile. For this reason, the pattern of phosphorus release and migration into the soil profile and the resulting increase in phosphorus concentration in the groundwater samples differed from the nitrogen release patterns. In comparison with 2007, total phosphorus concentration in the groundwater samples increased by 16% on average in 2008 and by 11% on average in 2009 in treatments fertilized with meat and bone meal (Table 6). The application of the highest rate of meat and bone meal (2.5 t ha^{-1}) contributed to the most significant increase in phosphorus concentration in groundwater. In the above treatment, phosphorus concentration increased more than two-fold and PO_4^{3-} concentration showed a nearly three-fold increase on average, relative to the control. The discussed treatment was also characterized by the highest variation in phosphorus levels between years. The most notable differences in average annual concentrations of PO_4^{3-} in groundwater samples were reported in the unfertilized treatment. The above can be attributed to relatively scarce vegetation cover in the unfertilized treatment, which resulted in significantly lower biosorption of phosphorus.

In the studied treatments, phosphorus concentrations in the groundwater samples were characterized by significant seasonal variation, and the above is indicative of the complex correlations between the type of fertilization, crop plant species, plant density and weather conditions, mostly the volume and distribution of precipitation in the growing season (Table 7). In most treatments, the lowest phosphorus concentrations were observed in the spring, in particular in the wettest year of 2007, when phosphorus compounds were strongly diluted with nutrient-deficient meltwater.

Significant correlations were observed between precipitation and total phosphorus concentrations in groundwater samples only in treatments fertilized with manure at the annual rate of 10 t ha^{-1}. As regards the more mobile phosphate compounds, increased precipitation led to intensified phosphate leaching in the unfertilized treatment and in plots fertilized with manure and the highest dose of meat and bone meal (Table 4).

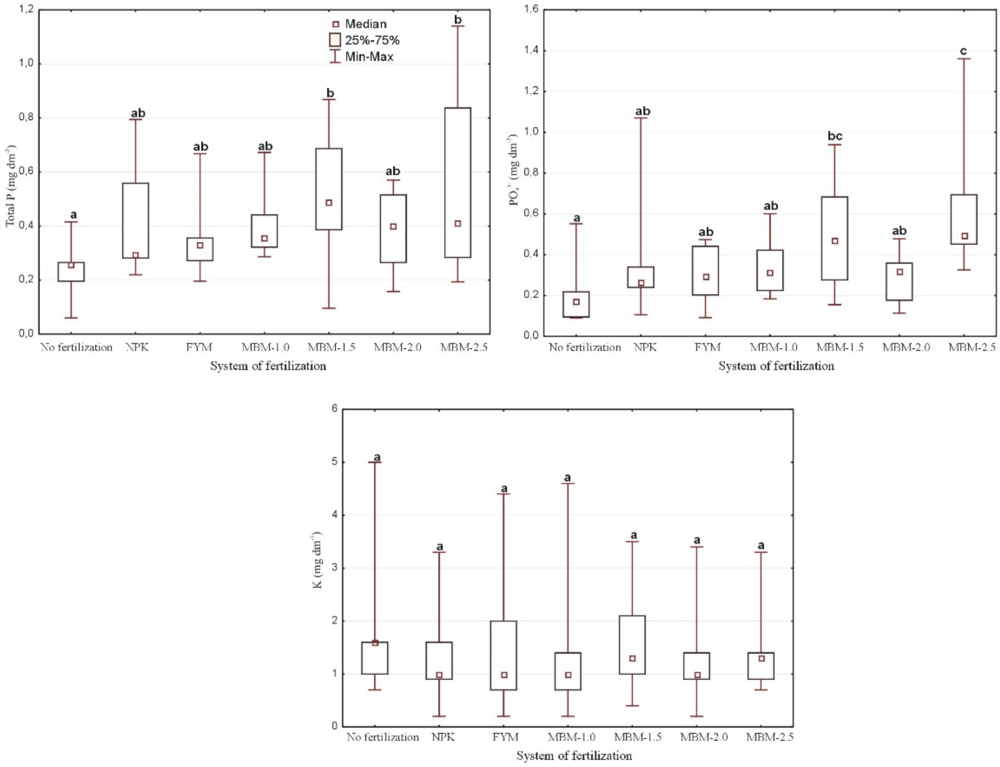

Fig. 2. The effect of soil fertilization regime on variations of phosphorus and potassium concentrations (mg dm^{-3}) in the groundwater (a,b …the values denoted with the same letter constitute a homogenous group and are not statistically significantly differentiated according to the Kruskal-Wallis test (α = 0.05))

Table 6. Average annual concentrations of phosphorus and potassium in groundwater, subject to the soil fertilization regime (mg dm^{-3})

Year	***System of fertilization***						
	No fertilization	***NPK***	***FYM***	***MBM-1.0***	***MBM-1.5***	***MBM-2.0***	***MBM-2.5***
Total P							
2007	0.22 a	0.43 b	0.40 b	0.43 b	0.43 b	0.30 ab	0.57 c
2008	0.30 a	0.36 a	0.32 a	0.35 a	0.45 a	0.41 a	0.79 b
2009	0.21 a	0.55 b	0.32 a	0.44 b	0.64 b	0.47 b	0.36 ab
Average	0.24 a	0.44 ab	0.35 ab	0.47 ab	0.51 b	0.39 ab	0.57 b
PO_4^{3-}							
2007	0.32 a	0.47 a	0.40 a	0.38 a	0.59 ab	0.32 a	0.71 b
2008	0.12 a	0.40 ab	0.25 a	0.20 a	0.31 a	0.28 a	0.81 b
2009	0.20 a	0.31 a	0.22 a	0.44 ab	0.59 b	0.25 a	0.48 b
Average	0.21 a	0.39 ab	0.29 ab	0.34 ab	0.50 bc	0.28 ab	0.67 c
K							
2007	2.90 b	2.10 a	2.23 ab	2.20 a	2.67 b	1.67 a	2.00 ab
2008	1.07 b	0.67 a	0.43 a	0.53 a	0.80 ab	0.73 ab	1.20 b
2009	1.50 a	1.20 a	2.03 b	2.33 b	1.37 a	1.90 b	1.07 a
Average	1.82 a	1.32 a	1.56 a	1.69 a	1.61 a	1.43 a	1.42 a

a,b …the values denoted with the same letter constitute a homogenous group and are not statistically significantly differentiated according to the Kruskal-Wallis test (α = 0.05)

Table 7. Average seasonal concentrations of phosphorus and potassium in groundwater, subject to the soil fertilization regime (mg dm^{-3})

Season	***System of fertilization***						
	No fertilization	***NPK***	***FYM***	***MBM-1.0***	***MBM-1.5***	***MBM-2.0***	***MBM-2.5***
Total P							
Spring	0.16 a	0.43 ab	0.27 ab	0.34 b	0.62 b	0.38 ab	0.53 b
Summer	0.23 a	0.45 ab	0.34 a	0.53 b	0.44 ab	0.38 ab	0.59 b
Autumn	0.33 a	0.46 ab	0.43 a	0.35 ab	0.46 a	0.42 a	0.59 b
PO_4^{3-}							
Spring	0.13 a	0.27a	0.26 a	0.27 a	0.56 ab	0.22 a	0.73b
Summer	0.30 a	0.20 a	0.21 a	0.41 ab	0.32 a	0.21 a	0.55 b
Autumn	0.21 a	0.70 b	0.41 ab	0.34 ab	0.61 b	0.42 ab	0.72 b
K							
Spring	1.10 a	1.13 a	1.60 b	0.93 a	1.73 b	1.70 b	1.13 a
Summer	2.50 ab	1.50 a	2.20 ab	3.10 b	1.63 ab	1.53 ab	1.83 ab
Autumn	1.87 b	1.33 ab	0.90 a	1.03 a	1.47 ab	1.07 a	1.30 ab

a,b …the values denoted with the same letter constitute a homogenous group and are not statistically significantly differentiated according to the Kruskal-Wallis test (α = 0.05)

In the analyzed groundwater samples, potassium concentrations were found in the range of 0.2 mg dm^{-3} (most treatments) to 5.0 mg dm^{-3} (control). No significant correlations between fertilization regime and potassium concentrations in groundwater were reported (Fig. 2). Although the treatments fertilized with meat and bone meal as well as with NPK were additionally supplied with potash salt in the amount of 83.1 kg K ha^{-1}, potassium concentrations in those plots were lower than those found in the unfertilized treatment (Table 6). The above could be attributed to the fact that the applied fertilizers met the potassium requirements of more developed and higher yielding plants, thus reducing the leaching of potassium to groundwater. A positive correlation was observed between precipitation volume in the growing season and potassium concentrations in groundwater samples – intense precipitation increased the rate at which potassium migrated into the soil profile and groundwater. The above correlation was statistically significant in the unfertilized treatment as well as in plots fertilized with manure and the highest dose of meat and bone meal.

4. Conclusions

The application of meat and bone meal at the rate of 1.0 to 2.0 t ha^{-1} with supplemental potassium fertilization does not lead to higher contamination of groundwater than mineral (NPK) fertilization. Crops grown on lessive soils should not be fertilized with meat and bone meal at rates higher than 2.0 t ha^{-1}. When higher doses of meat and bone meal are applied, unused nutrients are partially leached out of the soil profile into the groundwater, thus lowering groundwater quality. Meat and bone meal applied at the rate of 2.5 t ha^{-1} significantly increases the concentrations of mineral nitrogen and phosphate compounds in groundwater.

Meat and bone meal, a by-product of the meat processing industry, may be used as an alternative organic fertilizer provided that an appropriate cultivation technology is applied in observance of local weather conditions. In the growing seasons marked by optimal precipitation levels, the application of meat and bone meal at the rate of up to 2.0 t ha^{-1} does not contribute to groundwater contamination higher than mineral and farmyard manure fertilizers.

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