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The leaching of mineral nitrogen forms from light soil fertilized with compost and sewage sludge

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Abstract: The research was carried out in the years 2003–2013 in lysimeters filled with loamy sand. The leachate was tested in three variants: Z – no fertilization, S – 20 $g{\cdot}m^{-2}$ of N delivered annually in sewage sludge and C – 20 $g{\cdot}m^{-2}$ of N in the form of compost. The lysimeters were planted with *Miscanthus giganteus*, which is an energy plant with a high demand for water and nutrients. The amount of leaching of mineral nitrogen forms was determined on the basis of measured volumes of leachates from the soil and volumes of ammonium nitrogen ($N\text{-}NH_4$) and nitrate nitrogen ($N\text{-}NO_3$) contained in them. The research results showed a significant increase in the average content of mineral nitrogen forms in the effluents from the fertilized soil (S – 6.8 $mg{\cdot}dm^{-3}$ of $N\text{-}NO_3$ and 0.3 $mg{\cdot}dm^{-3}$ of $N\text{-}NH_4$, C – 7.8 $mg{\cdot}dm^{-3}$ of $N\text{-}NO_3$ and 0.4 $mg{\cdot}dm^{-3}$ of $N\text{-}NH_4$), compared to their concentrations in the leachates from non-fertilized soil (Z – 2.1 $mg{\cdot}dm^{-3}$ of $N\text{-}NO_3$ and 0.2 $mg{\cdot}dm^{-3}$ of $N\text{-}NH_4$). The content of mineral forms of nitrogen, in particular $N\text{-}NO_3$, were similar in both fertilization variants. The lowest concentrations of mineral nitrogen in the leachates occurred in the third and fourth year after planting *Miscanthus giganteus*, when it entered the period of the highest yield. In the fifth year, due to a cold, snowless winter, there was a weakened growth of plants, which resulted in an increase in the concentration of mineral nitrogen in the leachates from the fertilized soil. It follows that in addition to the intensity of precipitation, the collection of this component by plants primarily influences nitrogen leaching from the soil. The general amount of mineral nitrogen leached from the soil was not large and amounted Z – 2.5 $kg{\cdot}m^{-2}$, S – 6.7 $kg{\cdot}m^{-2}$, C – 6.4 $kg{\cdot}m^{-2}$. This testifies to the intense collection of this form of nitrogen by *Miscanthus giganteus*.

Keywords: mineral nitrogen, light soil, sewage sludge and compost

INTRODUCTION

Nitrogen that is in the soil, as well as that which is brought into it in the form of fertilizers, is not used entirely by plants. Its mineral forms are taken up by plants (Gorlach & Mazur 2002, Kozdraś 2006), but also washed away from the soil into groundwater (Rudzianskaite & Miseviciene 2005, Kozdraś & Czyżyk 2006, Sojka et al. 2008, Czyżyk & Rajmund 2014). Nitrogen in organic fertilizers, e.g. in composts from sewage sludge, occurs mostly in an organic form, and its mineral forms represent from a few to slightly over 20% of the total nitrogen content (Czyżyk & Kozdraś 2004, Krzywy-Gawrońska 2006). The organic nitrogen supplied to the soil undergoes complex and dynamic changes (Scholefield et al.1991, Fotyma 1996). As a result of these changes, especially in the nitrification process, mineral forms of nitrogen emerge, especially nitrates. $N\text{-}NO_3$ and $N\text{-}NH_4$ released in

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the mineralization process are used by plants and affect the growth of crops. However, their surplus penetrates into groundwater (Gotkiewicz 1996, Sapek 1996). Soil fertilization with sewage sludge or compost with nitrogen-rich sediments creates the threat of water contamination with mineral nitrogen forms, as does fertilization with other nitrogen fertilizers. The level of this threat depends on the size of the applied sludge or compost, but it is much smaller than in the conditions of fertilization with equivalent doses of mineral fertilizers (Czyżyk & Kozdraś 2008).

In order to reduce the surplus production of mineral nitrogen forms in the soil and their penetration into the depths and groundwater contamination, it is necessary to properly determine the doses of fertilizers, including nitrogen reserves in the soil, the type of fertilizers and nutritional needs of plants. It is especially necessary in annual fertilization, which may cause a significant surplus of nutrients in the soil and their penetration into groundwater. In practice, sewage sludge, as well as composts made out from it, is often used annually (usually in the neighborhood of sewage treatment plants). This raises concerns about the possibility of increasing groundwater pollution, especially with nitrates. In particular this applies to light soils in which the organic substance undergoes rapid mineralization and the products of this process are easily transferred into the soil profile.

The goal of the study was to determine the impact of annual soil fertilization with sewage sludge or compost on leaching mineral nitrogen forms from light soil and proving the need to determine reasonable doses of fertilization (including nitrogen reserves in soil).

MATERIALS AND METHODS

The research was carried out in 2008–2013 in lysimeters filled with loamy sand, containing an average 14% of sallow parts (fraction < 0.02 mm), 24.8% of dust parts (0.02–0.1 mm), 61.2% of sand (0.1–1.0 mm). The lysimeters conditions were close to those in the natural field. Lysimeters with a diameter of 100 cm and a depth of 130 cm were completely buried in the ground. The soil in lysimeters was fertilized annually with sewage sludge and compost. The sludge came from a mechanical-biological, rural sewage treatment plant which was stabilized and mechanically dehydrated. Compost from this sludge was produced annually. The same nitrogen doses of 15.7 g per lysimeter were provided into the soil, which is 20 $g \cdot m^{-2}$ of N in the sewage sludge (variant S) and compost (variant C). A control variant without fertilization was also used (variant Z). All variants were used in three repetitions. A nitrogen dose of 20 $g \cdot m^{-2}$ of N (200 $kg \cdot ha^{-1}$ of N) was adopted taking into account the great needs for nutrients for *Miscanthus giganteus*. This was a high dose, exceeding 170 $kg \cdot ha^{-1}$ of N, permissible in natural fertilizers (liquid manure, manure), specified in the Notice on fertilizers and fertilization (*Obwieszczenie*... Dz.U. 2017, poz. 668). However, Polish regulations do not limit nitrogen doses in mineral and organic fertilizers (sludge, compost). The use of a high dose of nitrogen in the tests made it possible to obtain more clear differences between the results of the fertilization variants.

In 2008, lysimeters were planted with *Miscanthus giganteus* which is characterized by a high demand for water and nutrients. During the research period, the amount of atmospheric precipitation and leachate from lysimeters was systematically measured and samples were taken for chemical analyzes. The analyzes were made using commonly used methods (Hermanowicz et al. 1999, A set of standards 1999).

The following were marked in the laboratory for the tested samples:

- granulometric composition by the Casagrande method modified by Prószyński,
- organic carbon (C_{org}) by the chromate method according to Tiurin,
- organic substance – roasting at 550°C,
- general nitrogen (N_{Tot}) according to Kjeldahl by calorimetric method,
- mineral forms of nitrogen ($N\text{-}NO_3$, $N\text{-}NH_4$) by calorimetric method, preceded by distillation separation of ammonia.

Computer software “Statistica 10” was used to statistically estimate the significance between the amounts of mineral nitrogen leaching in each individual variant. The significance between the amounts of washed out nitrogen was compared with the following pairs of variants: variant without fertilization with fertilized variants and sewage sludge with compost.

RESULTS AND DISCUSSION

The results of chemical analyses of materials used in the tests are given in Table 1. The content of total nitrogen and its forms in sewage sludge and compost varied. Differences in nitrogen and its forms in the sludge and compost were confirmed statistically.

In order to provide the soil with an equal dose of nitrogen in both fertilization methods, a greater amount of compost than sewage sludge was used. Therefore, the amount of organic matter supplied to the soil with compost was greater than the amount supplied with sewage sludge. This could have an impact on the reduction of leaching from soil when fertilized with compost. Leachates from the soil depend mainly on the amount of rainfall and the transpiration of plants during the growing season as well as the type of soil and its organic matter content.

The individual years of research differed significantly in terms of the amount of precipitation (Tab. 2). The volume of leachates from lysimeters varied, mainly depending on the amount of rainfall, and less on the fertilization variants and the type of fertilizers (Tab. 3).

Leachates from lysimeters occurred in the late autumn and winter periods. During the growing period, the volume of leachate was much smaller. Large volumes of leachate occurred only after heavy rainfall, e.g. in May 2010 and 2013, as well as in June 2009 and 2013. The leachates usually appeared from several hours to two days after precipitation, depending on the soil moisture status preceding them.

Table 1
The nitrogen content and its form in sewage sludge and compost

Year	**Fertilizer**	**Component [mg·g^{-1}·DM]**						**Organic matter**	**C:N**
		N_{Tot}	**N_{org}**	**N_{min}**	**N-NOx**	**N-NH_4**	**C_{org}**	**[%]**	
2008	S	52.2	47.4	4.8	0.53	4.26	307.3	76	6
	C	27.3	26.4	0.9	0.59	0.26	310.4	66	11
2009	S	53.3	48.6	4.6	0.13	4.51	297.3	70	6
	C	24.8	23.4	1.4	0.81	0.55	292.8	59	12
2010	S	65.9	64.5	1.4	0.23	1.14	311.4	72	5
	C	22.8	22.2	0.6	0.29	0.29	258.6	66	11
2011	S	50	47.6	2.4	0.24	2.2	328.5	71	7
	C	21.9	19.8	2.1	1.84	0.23	245.4	53	11
2012	S	45	41.8	3.2	0.32	2.84	255.1	64	6
	C	28.4	27.1	1.4	1.05	0.3	266.8	64	9
2013	S	54.5	49.8	4.7	0.55	4.1	304.4	73	6
	C	32.4	31	1.4	1.18	0.17	223	61	7
Avg ± S.D. of 6 years	S	53.5 ± 6.9	50.0 ± 7.6	3.5 ± 1.4	0.3 ± 0.2	3.2 ± 1.3	300.7 ± 24.6	71.0 ± 4	6.0 ± 0.6
	C	26.3 ± 3.9	25.0 ± 4.0	1.3 ± 0.5	1.0 ± 0.5	0.3 ± 0.1	266.2 ± 31.7	61.5 ± 5	10.2 ± 1.8
T-Test	S vs. C	0.000008**	0.00003**	0.00484**	0.02135*	0.00039**	0.06	0.00461**	0.00037**

Explanations: DM – dry matter; S – sewage sludge; C – compost; Avg – average; S.D. – standard deviation.

* Statistically significant at the level of $p < 0.05$.

** Statistically significant at the level of $p < 0.01$.

Table 2
Atmospheric precipitation at the research period in 2008–2013 [mm]

Year	Precipitation in months [mm]												Annual amount of precipitation
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
2008	61.7	12.5	44.8	82.5	35.0	45.7	50.7	103.6	28.8	42.2	29.2	15.8	552.3
2009	38.2	56.7	58.2	30.1	85.8	174.1	138.8	58.3	11.9	87.3	32.5	58.5	830.4
2010	47.8	10.3	37.0	60.5	169.2	42.5	97.3	129.7	132.2	5.0	73.5	66.9	871.7
2011	34.8	11.0	48.8	30.7	51.1	84.2	143.1	79.1	36.6	46.2	0.5	50.8	616.8
2012	59.5	38.9	12.3	27.8	66.2	106.8	100.2	72.6	56.9	43.7	32.1	24.6	641.4
2013	55.2	36.6	44.0	39.9	130.7	190.7	39.6	64.1	124.6	6.6	24.5	17.5	773.9
Sum	297.1	166.0	245.0	271.5	537.9	644.0	569.6	507.3	390.8	231.0	192.3	234.0	4286.4

Table 3
The sum of annual leachate volumes collected in the period 2008–2013 from particular fertilization variants [$dm^3 \cdot m^{-2}$]

Year	Z	S	C
2008	127.9	111.8	90.7
2009	255.4	238.0	217.0
2010	289.9	257.7	206.0
2011	95.4	80.3	52.6
2012	255.2	178.2	155.9
2013	382.7	266.0	190.3
Sum	1406.4	1131.9	912.5
T-Test Z vs. S	0.4184		
T-Test Z vs. C	0.1452		
T-Test S vs. C	0.4063		

Variants: Z – without fertilization, S – sewage sludge, C – compost.

Table 4
Averages annual and period 2008–2013 concentration of mineral forms ($N\text{-}NO_3$ and $N\text{-}NH_4$) from particular variants [$mg \cdot dm^{-3}$]

Year	Component	Variant		
		Z	S	C
2008	$N\text{-}NH_4$	0.23	0.39	0.34
	$N\text{-}NO_3$	7.9	22.4	23.3
2009	$N\text{-}NH_4$	0.22	0.38	0.43
	$N\text{-}NO_3$	1.3	5.0	6.0
2010	$N\text{-}NH_4$	0.21	0.26	0.37
	$N\text{-}NO_3$	0.6	1.0	2.0
2011	$N\text{-}NH_4$	0.15	0.26	0.29
	$N\text{-}NO_3$	0.5	2.0	3.0
2012	$N\text{-}NH_4$	0.17	0.24	0.25
	$N\text{-}NO_3$	1.2	4.7	9.0
2013	$N\text{-}NH_4$	0.21	0.26	0.49
	$N\text{-}NO_3$	0.9	5.4	3.2
Average 2008–2013	$N\text{-}NH_4$	0.20	0.30	0.36
	$N\text{-}NO_3$	2.1	6.8	7.8
T-Test Z vs. S	$N\text{-}NH_4$	0.000000*		
	$N\text{-}NO_3$	0.000029*		
T-Test Z vs. C	$N\text{-}NH_4$	0.000000*		
	$N\text{-}NO_3$	0.000001*		
T-Test S vs. C	$N\text{-}NH_4$	0.009957*		
	$N\text{-}NO_3$	0.448126		

Variants: Z – without fertilization, S – sewage sludge, C – compost.

* Statistically significant at the level of $p < 0.01$.

Table 4 presents the average content of nitrogen forms in the leachates from lysimeters. They were calculated as weighted averages from the volume of leachate and concentration of N-NO$_3$ and N-NH$_4$ in them. The contents of mineral nitrogen forms in the leachates from lysimeters varied depending on the fertilization variants. The content of N-NO$_3$ in the leachates from the soil fertilized with sewage sludge and compost, over the entire study period, was definitely higher than in the leachates from non-fertilized soil. In the first year of research (2008), when the plants were still slightly rooted after planting, the average content of N-NO$_3$ was large and in particular variants was: Z – 7.9 mg·dm^{-3} of N, S – 22.4 mg·dm^{-3} of N and C – 23.3 mg N·dm^{-3} of N. In conversion to nitrates, these are respectively: 34.9 mg·dm^{-3} of NO$_3$, 99.0 mg NO$_3$·dm^{-3} of NO$_3$ and 103.0 mg·dm^{-3} of NO$_3$. Comparing these values with the limits for groundwater cleanliness classes (*Rozporządzenie*... Dz.U. nr 143, poz. 896), it can be stated that in the control variant (Z) they corresponded to class III, and in variants with fertilization (S and C) up to the V quality class. In the following years, the content of nitrates in the leachates gradually decreased and were within the limits for the I and II water quality class. The lowest were in the third and fourth year of research (2010 and 2011) when *Miscanthus giganteus* entered the period of the highest growth. In the next two years, the content of N-NO$_3$ in the leachates in all variants has increased. It was caused by a significant weakening of *Miscanthus giganteus* plant growth due to the snowless and cold winter of 2012. Part of the plants extinct, and the remaining ones showed weaker development, and thus reduced absorption of ingredients. As a result there was an increase in the N$_{min}$ content in leachates from soil (Fig. 1). The high mobility of mineral nitrogen in the soil, under conditions of limited absorption by plants, may cause significant migration to groundwater (Gondek & Kopeć 2008).

In general, the content of nitrate nitrogen (N-NO$_3$) in the leachates was not large, despite the high nitrogen dose used in the sludge and compost (200 kg·ha^{-2} of N). The results of field research in the catchment used agriculturally, in similar soil and meteorological conditions, showed a mean concentration of N-NO$_3$ in drainage leachates of 20.2–32.5 mg·dm^{-3} (Pulikowski et al. 2012). These differences testify to the intensive absorption of this form of nitrogen released gradually from organic fertilizers in the process of mineralization by plants. The course and efficiency of the mineralization of organic nitrogen compounds depends mainly on humidity, temperature, pH, organic carbon content and soil type (Sapek 2010).

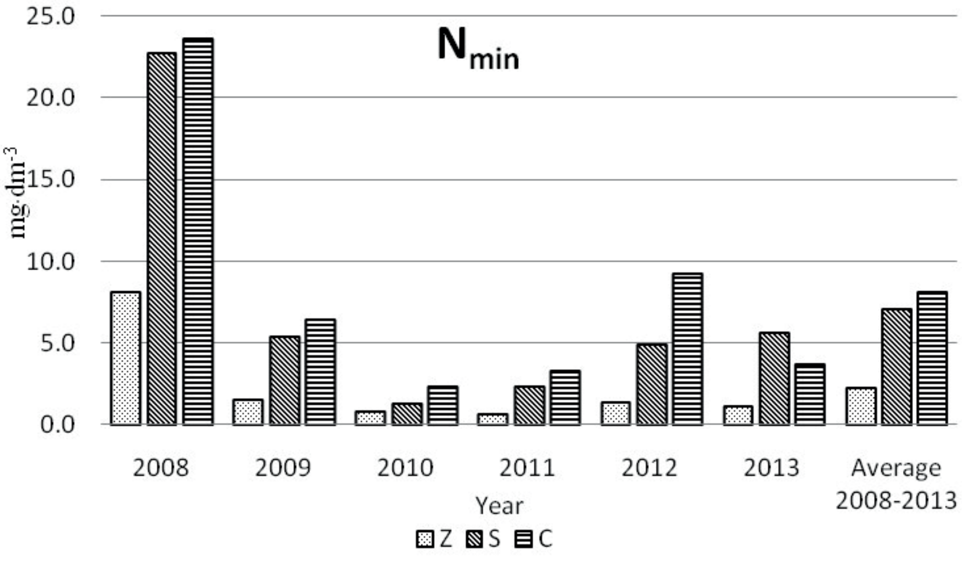


Fig. 1 *Average annual concentration of mineral nitrogen (N$_{min}$) in leachates from particular variants in the period 2008–2013 [mg·dm^{-3}]*

The contents of ammonium nitrogen (N-NH_4) in the leachates were different to that of nitrate nitrogen (N-NO_3) and were characterized by much smaller diversity. During the entire research period and in all variants, these were small contents not exceeding the level of groundwater purity for the I class. Ammonium nitrogen, like nitrate nitrogen, is taken up by plants. Ammonium nitrogen ions, in contrast to nitrate nitrogen, are additionally absorbed and bound by the soil sorption complex. In favorable humidity, air and thermal conditions, ammonium nitrogen is relatively quickly oxidized in the nitrification process to the nitrate nitrogen form, especially in light soils. In the conducted research, it was found that organic carbon and organic substances increased in soil fertilized with sewage sludge and compost (Tab. 5). It is a factor influencing the improvement of physical-chemical soil properties. As a result of this improvement, the sorption capacity of the soil increases and more different ingredients, including ions, are retained in it NH_4^+. The above mentioned factors are a reason that leaching of ammonium nitrogen from the soil is many times smaller than the leaching of nitrate nitrogens.

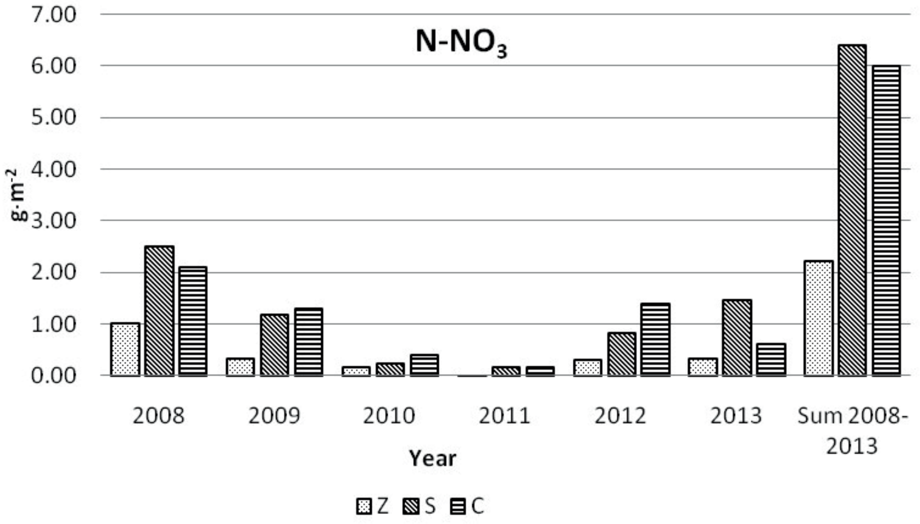
The reduced leaching of ammonium nitrogen also arose from the fact that soils generally contain much more N-NO_3 than N-NH_4. A five-year study by Kucharzewski & Nowak (2008) showed that the proportion of N-NO_3 accounted for more than 70% of the total mineral nitrogen content in the soils used for agriculture.

Quantities (load) of N-NO_3 and N-NH_4 released in the leachates throughout the research period (Fig. 2) showed a similar course as in the case of concentrations. In the total amount of mineral nitrogen released in the unfertilized soil (Z), the amount of nitrate form was around 8 times larger than the ammonium form (Tab. 4). In the fertilizer variants (S and C) these differences were even greater. The amount of nitrate form was about 20 times greater than the amount of ammonium form. In these variants, nitrates accounted for 95% of the mineral nitrogen leached from the soil. The total amount of nitrogen delivered to the soil in fertilizers and atmospheric precipitation, as well as that released in mineral form with leachates, was calculated. The amount of nitrogen delivered into the soil with precipitation was calculated as the weighted average of the volume of precipitation and the total nitrogen contained therein. The amount was on average 3.65 $g \cdot m^{-2}$ of N per year, that is 21.9 $g \cdot m^{-2}$ of N during 6 years of research. In the variant without fertilization (Z), the amount of mineral nitrogen washed out of the soil was 2.51 $g \cdot m^{-2}$ of N, which was 11.5% of the total nitrogen delivered to the soil with precipitation. A very high statistical significance between the amounts of leachated nitrogen in the Z variant was found, and the quantities in the fertilizer variants ($p < 0.01$).

Table 5
Some properties of the soil before and after studies

Variant	**Year**	**Content**			
		Organic substance	**C_{org}**	**N_{org}**	**P_{org}**
		[%]	**[$mg \cdot g^{-1} \cdot DM$]**		
Z	2008	16.4	6.72	0.79	0.39
	2013	16.2	5.66	0.77	0.35
	Increase	−0.2	−1.06	−0.02	−0.04
S	2008	16.1	6.89	0.73	0.37
	2013	19.9	8.31	0.87	0.55
	Increase	3.8	1.42	0.14	0.18
C	2008	15.3	6.53	0.86	0.37
	2013	20.8	7.68	0.98	0.52
	Increase	5.5	1.15	0.12	0.15

Variants: DM – dry matter Z – without fertilization, S – sewage sludge, C – compost.



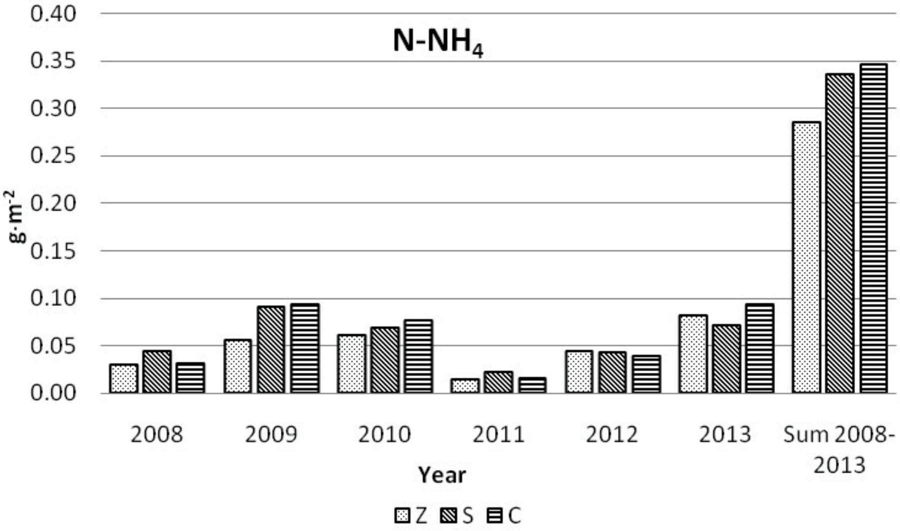


Fig. 2. *Annual sum of* $N\text{-}NO_3$ *and* $N\text{-}NH_4$ *load in leachate in the period 2008–2013 from particular variants* $[g{\cdot}m^{-2}]$

In variants of soil fertilization with sewage sludge (S) and compost (C), the amount of mineral nitrogen leaching was several times higher and was up to: S – 6.7 $g{\cdot}m^{-2}$ of N, C – 6.4 $g{\cdot}m^{-2}$ of N. There was no statistical significance between these amounts ($p = 0.71$). These results are in accordance with the ones obtained by Sądej et al. (2009). In their studies, sediment and compost doses at 10 $Mg{\cdot}ha^{-1}$, the amounts of mineral nitrogen leachates from the soil were 4.15 $kg{\cdot}ha^{-1}$ and 4.64 $kg{\cdot}ha^{-1}$ respectively. Leaching of mineral nitrogen from soil fertilized with sediment and compost expressed as a percentage of total nitrogen supplied to the soil. It was not large and accounted for: S – 4.7%, C – 4.5% (Tab. 6). In previous similar studies from soil fertilization with compost and mineral fertilizers, the mineral nitrogen leaching in crop rotation was much higher and was up to: 12% – variant with compost and 19–21% variant with mineral fertilizers (Czyżyk et al. 2011). This means that *Miscanthus giganteus* is a plant that extracts much more nitrogen than other crops. For most crops, an annual dose of 100 $kg{\cdot}m^{-2}$ of N (Czuba 1989) is recommended. In this research, 20 $g{\cdot}m^{-2}$ of N (200 $kg{\cdot}ha^{-1}$) dose was applied, and even though nitrogen leaching from the soil was twice as low. This proves the need to determine precisely the doses of fertilizers by adapting them to the plant's nutritional needs, but also taking into account the current abundance of soil in assimilable nutrients.

Table 6

The amount of total nitrogen (N_{Tot}) delivered to the soil and released in the leachate [g·m^{-2}] from particular fertilization variants

Form of nitrogen	**Unit**	**Amount in particular variants**		
		Z	**S**	**C**
Nitrogen in fertylisers	[g·m^{-2}]	0	120	120
Nitrogen from precipitation		21.9	21.9	21.9
Total nitrogen		21.9	141.9	141.9
Mineral nitrogen drained with leachate		2.5	6.7	6.4
	[%N_{Tot}]	11.4	4.7	4.5
T-Test Z vs. S	0.000166*			
T-Test Z vs. C	0.000062*			
T-Test S vs. C	0.710034			

Variants: Z – without fertilization, S – sewage sludge, C – compost.

* Statistically significant at the level of $p < 0.01$.

CONCLUSIONS

1. The concentration of mineral nitrogen in soil leachates is very variable and depends on the dose of fertilizers, meteorological conditions and the intensity of uptake by plants.
2. The degree of leaching of mineral nitrogen from soil fertilized with sewage sludge and compost is similar. There was no statistical significance in the amount of nitrogen washed out at an equivalent dose of nitrogen delivered to the soil in the sludge and compost.
3. The results of the research showed that a relatively high dose of nitrogen of 20 g·m^{-2} of N (200 kg·ha^{-1}), corresponds to the need of *Miscanthus giganteus* for this component. The amount of mineral nitrogen leached from the soil, both when fertilized with sewage sludge and compost, was small (less than 5% of total nitrogen supplied to the soil).
4. In order to limit the leaching of mineral nitrogen from the soil on which *Miscanthus giganteus* is cropped, the nitrogen dose should be adapted to the stage of development of the plant. When planting miscanthus, the nitrogen dose should be reduced. However, after entering the full yielding phase (3 and 4 years after planting), increased doses may be used.
5. From the soil fertilized with sewage sludge and compost, nitrate nitrogen is mainly wiped out ($N-NO_3$). In the total amount of mineral nitrogen leaching, it was as much as 95%.

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