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The relationship between nitrogen fertilizer forms and meteorological conditions on nitrogen transformation in the soil and loss via volatilization

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Abstract

The study was aimed to estimate the changes in ammonium (N-NH_4^+), nitrate (N-NO_3^-) and mineral (N-NH_4^+ + N-NO_3^-) nitrogen in the soil, nitrogen loss via volatilization and uptake as influenced by the nitrogen fertilizer form applied, soil moisture and temperature in the crop stand of the common wheat (*Triticum aestivum* L.) cultivar 'Skagen' during the tillering stage (BBCH 23–29). The crop was fertilized with surface-broadcast urea and ammonium nitrate (granular fertilizers). The soil of the experimental site is *Endocalcaric Endogleyic Luvisol* (WRB, 2014).

The content of N-NH_4^+ in the soil 7 days after winter wheat fertilization was found to be on average 25% higher in the plots applied with urea, while higher N-NO_3^- and N-NH_4^+ + N-NO_3^- contents, by 59% and 29%, respectively, were identified in the ammonium nitrate-applied plots. When winter wheat had been applied with ammonium nitrate or urea 4 days after resumption of spring growth, the contents of N-NH_4^+, N-NO_3^- and N-NH_4^+ + N-NO_3^- in the soil were significantly higher compared with the plots fertilized later, 8–16 days after beginning of spring growth. At winter wheat tillering stage, the content of N-NH_4^+ + N-NO_3^- in the soil was found to depend on soil temperature and moisture. The data of the multiple correlation analysis showed a strong relationship between N-NH_4^+ + N-NO_3^- content and soil temperature and moisture, significant at $P < 0.05$ level, in the winter wheat plots applied with ammonium nitrate ($R^2 = 0.719$) or urea ($R^2 = 0.879$). Volatilization of N-NH_3 in the winter wheat plots fertilized with ammonium nitrate was negligible and totalled 0.24%, while in the plots applied with urea it averaged 7.3%. Volatilization of N-NH_3 from urea depended on the soil temperature and moisture ($R^2 = 0.840$, $P < 0.05$).

In the plots fertilized with ammonium nitrate, the concentration of nitrogen in the above-ground part of winter wheat was higher, though not in all the treatments significantly, as compared with the urea-applied plots.

Key words: ammonium nitrate, mineral nitrogen forms, soil moisture, soil temperature, urea.

Introduction

Nitrogen is one of the most important nutrients for plant growth, development and productivity, and is a key factor ensuring the sustainability and economic viability of farming systems (Bardhan, Patel, 2016; Maheswari et al., 2017). The transformation of nitrogen compounds in the soil include mineralization, nitrification and denitrification, which are important processes for crop growth and environmental protection and are influenced by various environmental factors and agro technology (Asmala et al., 2011; Zeng et al., 2016). Research data suggest that about 40–50% of the nitrogen fertilizer applied to cropping systems is not absorbed by plants, but is lost to the environment as ammonia (N-NH_3), nitrate (N-NO_3^-), nitrous oxide (NO and N_2O) or molecular nitrogen (N_2) (Coskun et al., 2017). Numerous studies have reported that the emission of nitrogen compounds depends on the form and rates of fertilizers (Liu et al., 2014) and soil moisture (Wieder et al., 2011). Reichmann et al. (2013) have evidenced that increased precipitation may raise the ammonium (N-NH_4^+) vs nitrate (N-NO_3^-) ratio. Changes in this ratio are also influenced by soil temperature, because it affects microbial activity and nitrification rate in the soil (Thangarajan et al., 2015).

The biggest problem with the use of urea for crop fertilization is the control of ammonia (N-NH_3) volatilization into the atmosphere by preventing urea hydrolysis (Bolado Rodríguez et al., 2005). Suter et al. (2011) have indicated that the activity of urease communities increases with an increase in soil temperature.

In many studies, changes in N-NH_2, N-NH_4^+ and N-NO_3^- content have been found to be related to

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the ambient temperature, soil moisture and activity of microorganisms; however, there is no detailed answer to the question as to how the amount of these forms of nitrogen in the soil changes in the northern part of the temperate zone when winter wheat crop is of uneven development level during the tillering stage. Under different environmental conditions, nitrogen evaporation in the form of N-NH_3 varies from 0.9% to 29.8% (Pan et al., 2016), the data of San Francisco et al. (2011) suggest that it varies within up to 40% range; therefore it is important to evaluate these losses in a combination of excess moisture and below 12°C ambient temperature, i.e. at the beginning of winter wheat vegetation, when the highest nitrogen fertilizer rates are used. Holcomb et al. (2011) emphasized that as a result, it is difficult to predict precisely how much nitrogen will be lost in a given situation, which is influenced by climatic conditions and origin of the soil. The estimation of N-NH_3 loss during the main fertilization of winter wheat, i.e. at the tillering stage, when the highest nitrogen fertilizer rates are applied would facilitate decision taking regarding urea use at a specific crop growth stage. It is also important to consider, how the nitrogen form in the soil when fertilizing with different nitrogen fertilizers determines nitrogen uptake during the tillering stage. Determination of the relationships among all of the above factors would enable simulation of winter wheat fertilization at this stage in order to optimize nitrogen supply to plants and minimize environmental pollution by nitrogen compounds during the period of maximum risk of nitrate leaching. Subbarao et al. (2006) and Giola et al. (2012) also suggest that a better understanding of factors that influence nitrogen dynamics / transformation in the soil helps to increase N-use efficiency, and rationalization of fertilizer application can mitigate the negative effects on the environment.

The present study was aimed to estimate the changes of ammonium nitrogen (N-NH_4^+), nitrate nitrogen (N-NO_3^-) and mineral nitrogen (N-NH_4^+ + N-NO_3^-) in the soil, nitrogen loss via volatilization and nitrogen uptake as influenced by the nitrogen fertilizer forms, soil moisture and temperature in the crop stand of the common wheat (*Triticum aestivum* L.) cultivar 'Skagen' during the tillering stage (BBCH 23–29).

Materials and methods

Study site and experimental design. Field experiments were carried out during 2015–2018 at the Experimental Station (54°53′3.26″, 23°50′33.25″) of Aleksandras Stulginskis University (currently Vytautas Magnus University Agriculture Academy), Lithuania. The soil of the experimental field is Endocalcaric Endogleyic Luvisol (WRB, 2014). The plots were arranged in a randomised block design with four replications. Before the experiment, the pH_{KCl} value of the topsoil ranged from 6.8 to 7.2, the concentration of available phosphorus (P_2O_5) varied from 343 to 429 mg kg^{-1}, available potassium (K_2O) – from 157 to 242 mg kg^{-1}, organic carbon (C_{org}) content – from 1.43% to 1.63%. The mineral nitrogen (N-NH_4^+ + N-NO_3^-) content ranged from 2.77 to 4.96 and 8.48–8.54 mg kg^{-1}. The experiment exploring the changes in ammonium (N-NH_4^+), nitrate (N-NO_3^-) and mineral (N-NH_4^+ + N-NO_3^-) nitrogen in the soil and nitrogen (N-NH_3) loss via volatilization as influenced by the nitrogen fertilizer form applied, soil moisture and temperature in the crop stand of the winter wheat cultivar 'Skagen' during the crop tillering stage (BBCH 23–29) was carried out according to a two-factor design: factor A – fertilizer application time: beginning of spring growth of winter wheat (BBCH 23–25) – control, 4, 8, 12 and 16 days after resumption of spring growth; factor B – nitrogen fertilizer forms: ammonium nitrate and urea (granular fertilizers). Nitrogen fertilizer rate applied at the tillering stage was N_{90}. Winter wheat was additionally dressed with ammonium nitrate at the stem elongation stage N_{45} and heading stage N_{30}.

Experimental and analytical methods. The topsoil was analysed for pH_{KCl} measured in 1 N KCl extraction (potentiometric method), C_{org} was determined by the wet oxidation method, available P_2O_5 and available K_2O – by the Egner-Riehm-Domingo (A-L) method. The determination of N-NH_4^+ + N-NO_3^- content in the soil samples was performed in accordance with: N-NH_4^+ – by spectrophotometric, N-NO_3^- – by ionometric methods. The soil samples were collected from the 0–25 cm depth. Mineral nitrogen content in the soil was measured 7 days after each application of fertilizers. The total nitrogen content of plants was determined by the Kjeldahl method (ISO 5983-1:2005. Determination of nitrogen content and calculation of crude protein content - Part 1: Kjeldahl method) and expressed on a dry matter basis. Nitrogen content in the above-ground part of winter wheat plants was measured 7 days after each fertilizer application and at stem elongation stage (BBCH 30–32).

Soil temperature and moisture. Soil moisture content was measured at the 0–10 cm depth using a handheld soil moisture meter HH2 (Delta-T Devices, UK). Soil temperature was measured at the 0–10 cm depth at 9 a.m. The soil temperature and moisture were measured daily in six places of each treatment. The averaged data of soil temperature and moisture during the 7-day period from crop fertilization to soil sampling during the experimental period are presented in Table.

Volatilization of N-NH_3 was measured in the winter wheat crop applied with 90 kg ha^{-1} N as ammonium nitrate and urea at the winter wheat tillering stage using the vented chamber method (Yang et al., 2018). Immediately following fertilizer application, polyvinyl cylinder (0.3 m diameter and 0.2 m height) was placed in each plot and sealed at the bottom using soil to prevent losses of ammonia through seepage. The cylinder / apparatus contained two sponges (0.025 m foam) diameter. The N-NH_3 concentration in the cylinders was determined 7 days after fertilization with a hand pump Dräger Accuro (Dräger Safety AG & Co. KGaA, Germany) using

Table. Soil temperature and moisture during the experimental period

Fertilizer application time	Temperature °C			Moisture %		
	2016	2017	2018	2016	2017	2018
BBCH 23–25 (beginning of spring growth)	6.4	7.7	6.4	34.0	32.1	32.5
After 4 days	10.4	10.2	10.4	29.9	32.3	28.51
After 8 days	13.5	11.1	12.8	28.8	31.2	24.7
After 12 days	11.6	10.6	12.0	29.5	31.4	26.5
After 16 days	11.9	8.1	11.6	32.0	31.2	28.6

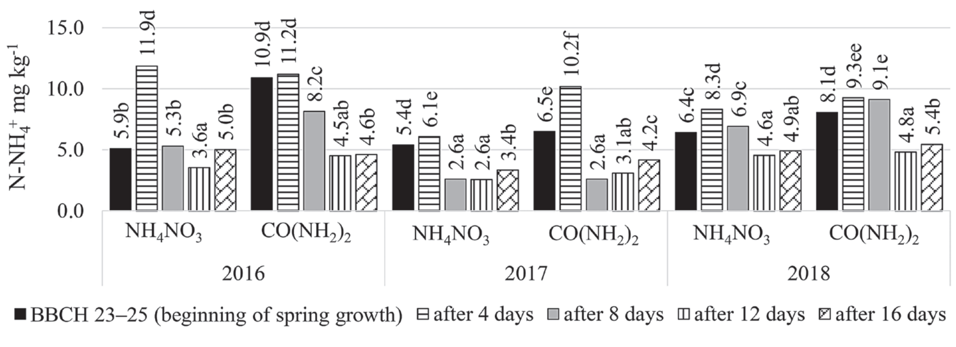
Dräger gas detection tubes (ISO 9001:2008. Quality management systems). The Dräger accuro is a bellows pump, with which the air sample is drawn through the Dräger tube using strokes. The air is drawn automatically and the gas sample to be measured is sucked through the tube being used. The Dräger-Tube pump accuro draws in 100 ml per stroke. Each Dräger-Tube contains a very sensitive reagent system that produces accurate readings when the technical characteristic of the gas detector pump precisely match the reaction kinetics of the reagent system in the tube. The substance conversion in the Dräger-Tube is proportional to the mass of the reacting gas. A test system, which reacts by changing colour when it comes into contact with a gas, is located on a solid carrier material within an enclosed gas tube – the Dräger-Tube. The scale on the tube allows evaluating the concentration of the ammonia directly after the measurement. The Dräger-Tube pump accuro complies with the requirements of DIN EN 1231 (Dräger Safety AG & Co. KGaA). NH_3 was recalculated as a percentage of N applied.

Statistical analysis. The statistical analysis of the experimental data was performed by the two-way analysis of variance (*ANOVA*) using the software *Selekcija* (Raudonius, 2017). The plots were arranged in a randomised block design. The significances of the differences between the treatments were evaluated using the Fisher protected least significant difference (LSD) test ($P \leq 0.05$). There was significant interaction between fertilization time (Factor A) and fertilizers forms (Factor B) therefore the averages of the factors A and B not presented. The correlation coefficients and relationships between the N-NH_4^+, N-NO_3^-, N-NH_3 and soil temperature, moisture ($n_{\text{number of pairs}} = 15$); nitrogen concentration in the winter wheat leaves and soil temperature, moisture, mineral nitrogen content ($n_{\text{number of pairs}} = 15$) tested were determined using the software *Statistica*, version 7 (Hill, Levicki, 2005).

Results and discussion

The experimental findings suggest that due to the different nitrogen fertilizer forms, fertilization time and contrasting meteorological conditions, the content of N-NH_4^+ in the soil cropped with winter wheat varied within 2.6–11.9 mg kg^{-1} range (Fig. 1). Spohn et al. (2016) have also emphasized that the concentrations of N-NH_4^+ and N-NO_3^- in soil solutions are variable and dynamic.

In many cases, the highest and statistically proven N-NH_4^+ content was determined in the soil fertilized with ammonium nitrate or urea 4 days after beginning of spring growth as compared to all other application timings. The obtained data are statistically significant compared with the content of N-NH_4^+ in the soil fertilized at beginning of spring growth, 8, 12 and 16 days after resumption of spring growth. The reduction of ammonium nitrogen in the subsoil area is likely to have occurred due to an increase in the mass of the root system, as formation of the secondary root system occurs during this period (Saidi et al., 2010), and namely this resulted in a more intensive nitrogen uptake. This is likely to be also associated with a 4°C increase in the soil temperature (10.2–10.4°C), a 4% decrease in the soil moisture and intensified microbial activity of *Bacillus*, *Clostridium*, *Proteus*, *Pseudomonas* and *Streptomyces*, *Micrococcus* spp., which take part in the ammonification processes. Saeed and Sun (2012) also suggest that the ammonification rate doubles with a 10°C temperature increase. The effect of meteorological conditions on the changes in N-NH_4^+ content has also been emphasised by Kabala et al. (2017). The correlation analysis of the data collected showed that the relationship of N-NH_4^+ content with the multiple effect of soil temperature and moisture was strong ($R^2 = 0.789_{NH_4NO_3}$, $P \leq 0.05$) and very strong ($R^2 = 0.848_{CO(NH_2)_2}$, $P \leq 0.05$). The greatest changes in N-NH_4^+ content as influenced by the aforementioned factors were determined at the beginning of spring growth of winter wheat and 8 days after spring growth resumed. During this period, the correlation between these indicators was very strong for both ammonium nitrate fertilization treatments ($R^2 = 0.988_{NH_4NO_3}$, $P \leq 0.05$) and urea fertilization treatments ($R^2 = 0.969_{CO(NH_2)_2}$, $P \leq 0.05$).



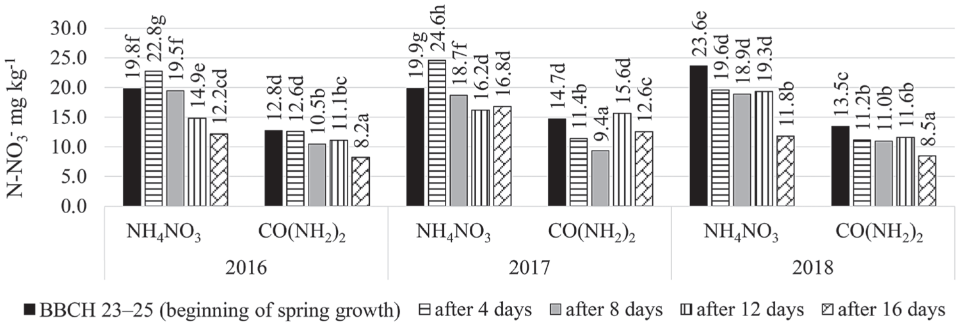
Note. Values followed by the same letters are not significantly different ($P > 0.05$); factor A – fertilizer application time, factor B – nitrogen fertilizer forms.

Figure 1. The influence of nitrogen fertilizer form and application time on the ammonium nitrogen (N-NH_4^+) content in the soil

The content of N-NH_4^+ in the soil was on average 25% higher in the urea-applied treatments as compared with ammonium nitrate-applied treatments. This is probably due to the chemical composition of fertilizers and the fact that urea and ammonium are converted to nitrate at different intensity.

The data of our study show that significantly higher concentrations of N-NO_3^- accumulated in the soil of winter wheat fertilized with ammonium nitrate (Fig. 2).

In the ammonium nitrate-applied plots the content of N-NO_3^- in the soil averaged (2016–2018) 17.8–19.2 mg kg^{-1}, and in the urea-applied plots – 11.0–12.4 mg kg^{-1}. This could be due not only to different ion forms in fertilizers, but also due to N-NH_2 and N-NH_4^+ transformation to N-NO_3^- time. This agrees with



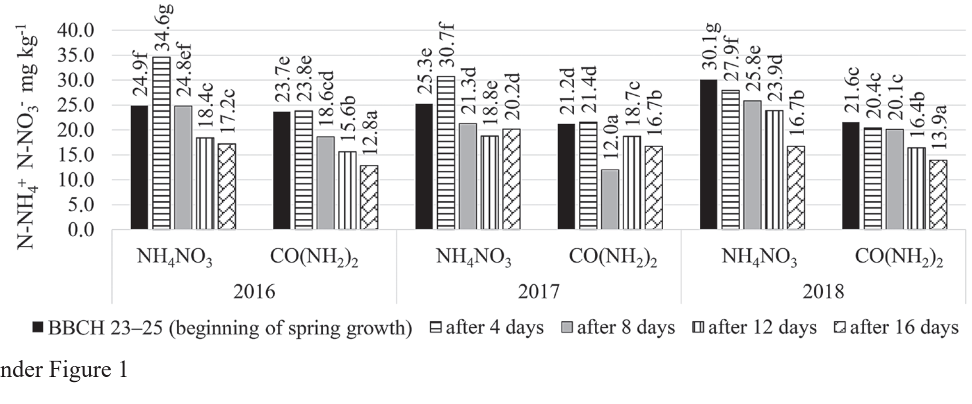
Explanation under Figure 1

Figure 2. The influence of nitrogen fertilizer form and application time on the nitrate nitrogen (N-NO$_3^-$) content in the soil

Jarvis et al. (2011) data suggesting that the differences in N-NO$_3^-$ content result from fertilizer forms. Our experimental findings evidenced that fertilizer application time (different climatic conditions – soil temperature and moisture) also had significant effect on the content of N-NO$_3^-$ in the soil. This is in line with the findings of other researchers who found that urea and ammonia are converted to nitrate at different rates depending on the climatic conditions (Jarvis et al., 2011). In 2016, when winter wheat had been fertilized with ammonium nitrate or urea 4 days after beginning of spring growth, and in 2018 at the beginning of spring growth significantly higher content of N-NO$_3^-$ accumulated in the soil, compared with those accumulated in the soil fertilized 8, 12 and 16 days after beginning of spring growth. The causality of changes in N-NO$_3^-$ content and other forms of nitrogen during the tillering stage has been explained in the studies of Lynch (2013) and Kiba and Krapp (2016), which suggest that efficient N uptake depends on root length, root size and distribution in the soil profile.

It was found that the correlation between the content of N-NO$_3^-$ and soil temperature at the beginning of spring growth and 4 days later was moderate ($R^2 = 0.330_{NH_4NO_3}$, $P \leq 0.05$) and strong ($R^2 = 0.777_{CO(NH_2)_2}$, $P \leq 0.05$), in the treatments fertilized 8, 12 and 16 days after beginning of spring growth this correlation was weak ($R^2 = 0.198_{NH_4NO_3}$, and $R^2 = 0.162_{CO(NH_2)_2}$, $P \leq 0.05$). The multiple correlation analysis showed a strong correlation of N-NO$_3^-$ with soil temperature and moisture ($R^2 = 0.711_{NH_4NO_3}$ and $R^2 = 0.798_{CO(NH_2)_2}$, $P \leq 0.05$). Based on our findings, the proposition of Sierra et al. (2015) suggesting that "the maximum concentrations of nitrates may result from the high temperatures of the air and soil that foster fast mineralisation of organic matter from crop remains" maybe further elaborated by stating that the content of N-NO$_3^-$ in the soil depends not only on the temperature but also on soil moisture and fertilizer application time. The reduction of N-NO$_3^-$ content in the soil fertilized 8 days after beginning of spring growth may be associated with the higher intensity of nitrogen uptake by plants. Gabriel et al. (2012) suggest that the increase in the concentration of N-NO$_3^-$ is usually linked to the decreased absorption of nitrates by agricultural crops. In 2017, the content of N-NO$_3^-$ in the soil varied inconsistently in response to urea fertilization time, although significant differences were obtained.

According to the data from the three experimental years, the highest N-NH$_4^+$ + N-NO$_3^-$ content was determined in the soil where winter wheat was fertilized with ammonium nitrate at the beginning of spring growth (in 2018) and 4 days later (in 2016 and in 2017). During this period, the impact of ammonium nitrate on the content of mineral nitrogen in the soil was significant compared with fertilization at later times and with urea application (Fig. 3). The effect of urea on mineral nitrogen content in the soil depending on the fertilization time was similar when it had been applied at the beginning of spring growth and 4 days later. In all the cases when winter wheat had been fertilized later (16 days after beginning of spring growth), mineral nitrogen content in the soil was markedly lower compared with the above discussed cases. Sapek and Sapek (2007) indicate that the content of nitrogen in the soil decreases due to plant and microorganism uptake. This explains the reduction of mineral nitrogen at a later period in our experiment.



Explanation under Figure 1

Figure 3. The influence of nitrogen fertilizer form and application time on the mineral nitrogen (N-NH$_4$ + N-NO$_3^-$) content in the soil

Mazur and Mazur (2015) suggest that the fertilizers applied could influence the content of mineral forms of nitrogen in the soil. Based on the data of individual years of the experiment and on averaged data, mineral nitrogen content in the soil 7 days after fertilizer application was significantly lower in the winter wheat plots applied with urea compared with the plots applied with ammonium nitrate. This could only be due to the partial transformation of $N\text{-}NH_2$ to $N\text{-}NH_4^+$ or $N\text{-}NO_3^-$ during this period. In this case, higher nitrogen volatilization from urea inappreciably changed mineral nitrogen content in the soil, as the correlation between these variables, when the soil temperature varied within 6.4–11.5°C and soil moisture within 24.7–34.0% range, was weak ($R^2 = 0.13$) and insignificant.

The multiple correlation regression analysis showed that in the winter wheat plots fertilized with ammonium nitrate the correlation of $N\text{-}NH_4^+ + N\text{-}NO_3^-$ content with soil temperature and moisture was strong ($R^2 = 0.719$) and significant and varied according to the equation: $y = 51.0918 - 0.73584x_1 - 0.78259x_2$. In the plots fertilized with urea this correlation was also strong ($R^2 = 0.879$) and significant, mineral nitrogen varied according to the equation: $y = 68.7906 - 1.6698x_1 - 1.22632x_2$. According to Glina et al. (2016), the mineral nitrogen level, nitrogen uptake, transformation, and leaching of particular nitrogen forms are influenced by temperature and moisture. Wieder et al. (2011) suggest that changes in precipitation can affect soil nitrogen cycling and balance.

Numerous studies suggest that ammonia ($N\text{-}NH_3$) volatilization is a major pathway of nitrogen (N) losses in agricultural systems from urea. Research suggests that surface soil moisture at the time of urea application and rainfall after application play the biggest role in affecting volatilization loss (Pan et al., 2016). Our study showed that when winter wheat had been fertilized with urea at different periods of BBCH 23–29 growth stage, nitrogen loss via volatilization varied within 5.5–9.4% range, on average 7.3% (Fig. 4).

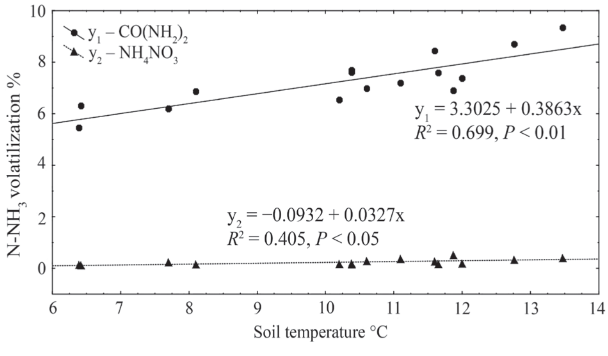


Figure 4. The relationship between ammonia ($N\text{-}NH_3$) volatilization and soil temperature

The data of the correlation regression analysis showed that the relationship between $N\text{-}NH_3$ nitrogen volatilization from the urea-applied plots of winter wheat and soil temperature was significant ($P \leq 0.01$) and strong ($R^2 = 0.699$), described by a linear equation: $y_1 = 3.3025 + 0.3863x$. The results of the correlation regression analysis show that the above mentioned indicators and their interaction can influence 70% of nitrogen volatilization from urea in $N\text{-}NH_3$ form. Rochette et al. (2013) suggest that volatilization of $N\text{-}NH_3$ from urea has been known to be directly dependent on ambient temperature, soil moisture, abundance of Uro bacteria and other factors.

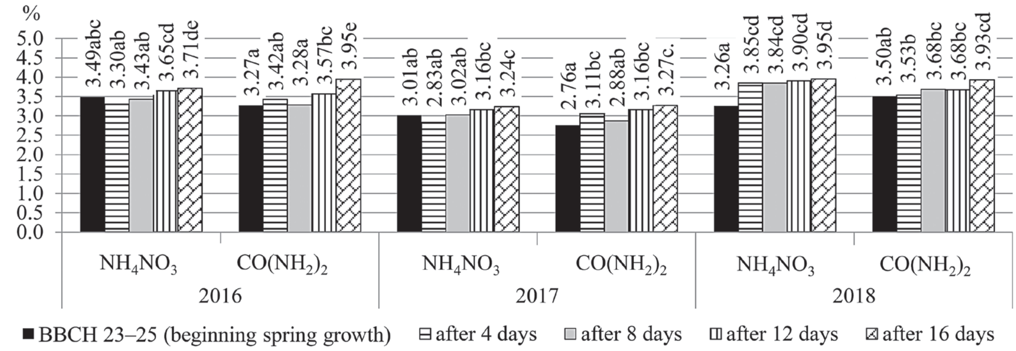
From Figure 4 one can see that $N\text{-}NH_3$ volatilization from urea, depending on the temperature, increased inconsistently. Analysis of the changes in nitrogen volatilization based not only on soil temperature but also on soil moisture revealed that in the case of higher soil moisture and higher soil temperature, the volatilization of nitrogen from the soil is close to that which occurs at lower temperatures and lower soil moisture. Holcomb et al. (2011) suggests that urea application during cool periods is no longer thought to ensure minimal volatilization loss, as nitrogen volatilization also depends on soil moisture. In our experiment, the highest $N\text{-}NH_3$ nitrogen volatilization loss from urea occurred at 13.5°C soil temperature and 28.8% soil moisture (Table). Compared with other cases, the increase of volatilization was significant. The lowest nitrogen loss via volatilization occurred at soil moisture above 30% and soil temperature up to 10°C. In these cases, volatilization losses of $N\text{-}NH_3$ were on average 33% lower compared with the highest value determined in the experiment. Eckard et al. (2003) have found that at high soil temperature and insufficient soil moisture content, the $N\text{-}NH_3$ loss from urea may reach 29%, in Schwenke et al. (2014) study – 11%. Franzen et al. (2011) have documented that at 20–25°C air temperature, $N\text{-}NH_3$ volatilization from urea over a 7-day period may reach 35%.

The data of the correlation regression analysis showed that the relationship between $N\text{-}NH_3$ nitrogen volatilization from the urea-applied plots of winter wheat and soil temperature and moisture was significant ($P \leq 0.05$) and very strong ($R^2 = 0.840$), described by a linear equation: $y = 19.8866 + 0.0895x_1 - 0.4405x_2$. In all experimental years, significantly higher $N\text{-}NH_3$ content was lost via volatilization from urea compared with ammonium nitrate.

When winter wheat had been fertilized with ammonium nitrate during the winter wheat growth stage BBCH 23–29, nitrogen losses were insignificant and amounted to 0.12–0.51% (on average 0.24%). Holcomb et al. (2011) have also indicated that volatilization loss from ammonium nitrate is very low, often similar to unfertilized controls. Although volatilization loss from ammonium nitrate during winter wheat tillering stage was low, it also depended on soil temperature and moisture. The relationship between these indicators was very strong ($R^2 = 0.849$) and significant ($P \leq 0.05$), and was described by the equation: $y = 0.1720 + 0.0046x_1 - 0.0015x_2$. The correlation regression analysis suggests that the above mentioned soil factors and their interaction can lead to 85% nitrogen volatilization from ammonium nitrate. Based on the results of this study, it is possible to quantify nitrogen volatilization when the soil temperature (°C) varies within $6.4 < x > 13.5$, and soil moisture (%) $24.7 < x > 34.0$ range and to predict it when calculating nitrogen balance.

The contents of $N\text{-}NH_2$, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ in the soil during winter wheat tillering stage depend on the soil nitrogen transformation, which is influenced by many environmental and anthropogenic factors, fertilization time and fertilizer forms.

Our experimental findings suggest that nitrogen concentration in the leaves of winter wheat fertilized with ammonium nitrate or urea decreased during the periods of tillering stage. In 2016 and 2017, nitrogen concentration in leaves was significantly higher in the winter wheat treatments fertilized with ammonium nitrate or urea at the beginning of spring growth and 4 days later compared with fertilization at later dates (Fig. 5). In 2018, the highest nitrogen content in leaves was accumulated by the winter wheat fertilized on the 8th day after resumption of spring growth, when the average air temperature within a 7-day period after fertilization was 10.4°C, which was in contrast to the trend of nitrogen concentration variation established in previous years. The significant reduction in nitrogen concentration at the beginning of spring growth in 2018 is likely to have been influenced by the negative air temperature (−0.7°C) during a 7-day period after fertilization, which suggests that nitrogen concentration in plants during this period is also highly dependent on the ambient temperature.



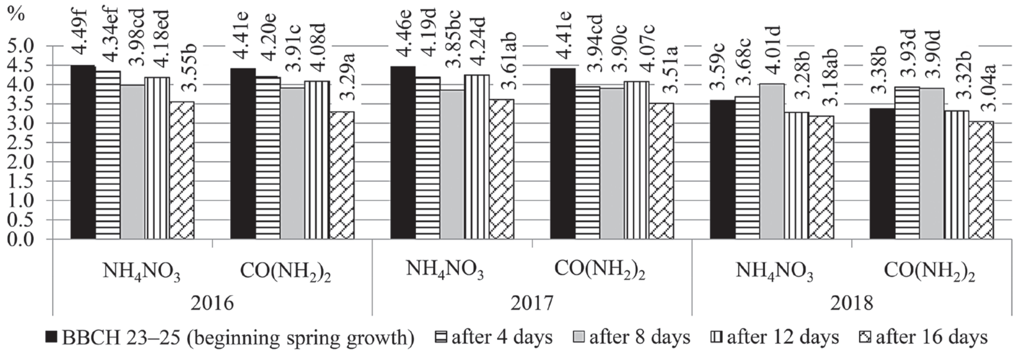
Explanation under Figure 1

Figure 5. The influence of nitrogen fertilizer form and application time on the concentration of nitrogen in the dry matter of winter wheat leaves at the BBCH 25–29 growth stage

The nitrogen fertilizer forms tested insignificantly changed, i.e. showed a trend towards changing, the concentration of nitrogen in plants. The experimental data showed that nitrogen uptake from the soil within a 7-day period after fertilization was more intensive in the ammonium nitrate-applied winter wheat plots compared with the urea-applied plots. The lower uptake of nitrogen from urea might have been determined by the weak activity of *Uro*, *Nitrosomonas* and *Nitrobacter* bacteria that transform the amide nitrogen form into N-NH$_4^-$ and N-NO$_3^-$, i.e. into the forms readily available to plants, in the conditions of lower ambient and/or soil temperature. The causality of these indicators is indicated by Suter et al. (2011) and Thangarajan et al. (2015).

At a later period, in the urea-applied winter wheat plots, the lower nitrogen concentration in leaves (dry matter) might have resulted from higher nitrogen volatilization losses (Fig. 4). The multiple correlation regression analysis indicated that the correlation between soil temperature (x_1), moisture (x_2), mineral nitrogen content (x_3) and nitrogen concentration (y) in the winter wheat leaves was significant ($P \leq 0.05$) and very strong ($R^2_{NH_4NO_3} = 0.972$ and $R^2_{CO(NH_2)_2} = 0.951$), and was described by the following equations: $y_{NH_4NO_3} = 4.117 - 0.059x_1 + 0.026\ x_2 - 0.002\ x_3$ and $y_{CO(NH_2)_2} = 2.685 - 0.009x_1 + 0.031\ x_2 - 0.025\ x_3$.

It was found that nitrogen concentration in winter wheat at the stem elongation stage (BBCH 30–32) did not change significantly in response to the nitrogen forms applied at the tillering stage. When winter wheat had been fertilized with ammonium nitrate at the tillering stage, the concentration of nitrogen in plants at the stem elongation stage was on average 1.2% higher than that in urea-fertilized plants. Irrespective of the fertilizer form used, with a delay in fertilizing, the concentration of nitrogen in plants showed a trend towards increasing (Fig. 6).



Explanation under Figure 1

Figure 6. The influence of nitrogen forms and application time on the concentration of nitrogen in the dry matter of winter wheat leaves at the BBCH 30–32 stage

At the stem elongation stage, the highest concentration of nitrogen in the above-ground part of winter wheat plants was established in the plots fertilized with both nitrogen fertilizers 12 and 16 days after beginning of spring growth. The correlation between the above mentioned indicators was strong ($R^2 = 0.739$)

and significant ($P \leq 0.05$). The weakest correlation was established between nitrogen content in plants at the stem elongation stage and beginning of spring growth ($R^2 = 0.376$). Averaged data suggest that the correlation between nitrogen concentration in plants at the stem elongation stage and nitrogen concentration in plants at the tillering stage was moderately strong ($R^2_{NH_4NO_3} = 0.339$ and $R^2_{CO(NH_2)_2} = 0.465$) ($P \leq 0.05$).

Conclusions

1. Seven days after winter wheat fertilization, the content of ammonium ($N\text{-}NH_4^+$) nitrogen in the soil were on average 25% higher in the urea-applied plots, while the concentrations of nitrate ($N\text{-}NO_3^-$) and mineral ($N\text{-}NH_4^+ + N\text{-}NO_3^-$) nitrogen in the soil were 59% and 29% higher, respectively, in the ammonium nitrate-applied plots.

2. In the plots of winter wheat fertilized with ammonium nitrate or urea, 4 days after beginning of spring growth, the contents of $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ and $N\text{-}NH_4^+ + N\text{-}NO_3^-$ in the soil were significantly higher than those in the winter wheat plots fertilized 8–16 days after beginning of spring growth.

3. At the winter wheat tillering stage, the content of $N\text{-}NH_4^+ + N\text{-}NO_3^-$ in the soil depended on the soil temperature and moisture. The multiple correlation analysis showed that in ammonium nitrate-applied winter wheat plots and urea-applied plots, $N\text{-}NH_4^+ + N\text{-}NO_3^-$ content strongly and significantly correlated ($P \leq 0.05$) with the soil temperature and moisture ($R^2_{NH4NO3} = 0.719$ and $R^2_{CO(NH2)2} = 0.879$).

4. The loss of $N\text{-}NH_3$ via volatilisation in the winter wheat plots fertilized with ammonium nitrate was negligible 0.24%, while in the urea-applied plots it averaged 7.3%. Volatilization of $N\text{-}NH_3$ nitrogen from urea depended on soil temperature and moisture ($R^2 = 0.840$, $P \leq 0.05$).

5. In the ammonium nitrate fertilization plots, the concentration of nitrogen in the above-ground part of winter wheat plants was higher but not in all the cases significantly, compared with the urea fertilization plots. Nitrogen concentration in the above-ground part of winter wheat was found to depend on soil temperature, moisture and soil mineral nitrogen content. The correlation among these indicators was very strong ($R^2_{NH4NO3} = 0.972$ and $R^2_{CO(NH2)2} = 0.95$) and significant ($P \leq 0.05$).

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Azoto transformacijos dirvožemyje ir išgaravimo ryšys prklausomai nuo azoto trąšų formos, tręšimo laiko ir meteorologinių sąlygų

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Santrauka

Tyrimo tikslas – įvertinti amoniakinio (N-NH$_4^+$), nitratinio (N-NO$_3^-$) ir mineralinio (N-NH$_4^+$ + N-NO$_3^-$) azoto pokyčius dirvožemyje, azoto išgaravimą ir jo įsisavinimą priklausomai nuo azoto trąšų formos, dirvožemio drėgmės ir temperatūros paprastojo kviečio (*Triticum aestivum* L.) veislės ‘Skagen’ krūmijimosi (BBCH 23–29) tarpsniu. Augalai tręšti karbamidu ir amonio salietra. Tyrimas atliktas limnoglacialinio lengvo priemolio ant moreninio molio karbonatingame giliau glėjiškame išplautžemyje (IDg4-k).

Nustatyta, kad po žieminių kviečių tręšimo praėjus 7 dienoms, N-NH$_4^+$ kiekis dirvožemyje buvo vidutiniškai 25 % didesnis patręšus karbamidu, o N-NO$_3^-$ ir N-NH$_4^+$ + N-NO$_3^-$ kiekiai didesni (atitinkamai 59 ir 29 %) patręšus amonio salietra. Žieminius kviečius nuo vegetacijos pradžios praėjus 4 dienoms patręšus amonio salietra arba karbamidu, N-NH$_4^+$, N-NO$_3^-$ ir N-NH$_4^+$ + N-NO$_3^-$ kiekiai dirvožemyje buvo esmingai didesni nei augalus patręšus vėliau – nuo vegetacijos pradžios praėjus 8–16 dienų. Augalų krūmijimosi tarpsniu N-NH$_4^+$ + N-NO$_3^-$ kiekis dirvožemyje priklausė nuo jo temperatūros ir drėgnio. Daugianarės koreliacinės analizės duomenimis, žieminius kviečius tręšiant amonio salietra arba karbamidu, N-NH$_4^+$ + N-NO$_3^-$ priklausomumas nuo dirvožemio temperatūros ir drėgnio buvo stiprus (R^2_{NH4NO3} = 0,719 bei $R^2_{CO(NH2)2}$ = 0,879) ir esminis ($P \leq 0{,}05$). Žieminius kviečius patręšus amonio salietra, azoto junginių (N-NH$_3$) išgaravimas buvo nežymus – 0.24 %, o tręšiant karbamidu siekė vidutiniškai 7,3 %. N-NH$_3$ išgaravimas iš karbamido priklausė nuo dirvožemio temperatūros ir dirvožemio drėgnio (R^2 = 0,840, $P \leq 0{,}05$). Augalus tręšiant amonio salietra žieminių kviečių antžeminėje dalyje azoto koncentracija buvo didesnė, nors ir ne visais atvejais esminė.

Reikšminiai žodžiai: amonio salietra, dirvožemio drėgmė, dirvožemio temperatūra, karbamidas, mineralinio azoto formos.