SOIL MINERAL NITROGEN DYNAMICS IN RELATION TO TILLAGE METHODS AND CROP ROTATION

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Abstract

The aim of the present study was to clarify the effect of conventional and reduced tillage and crop sequences on mineral nitrogen ($N_{min.}$) turnover in soil, including its seasonal and temporal variations, and distribution in soil profile. The experiment was carried out in 2012–2016 in Cambic Calcisol (Aric, Endohypocalcic, Ochric, Endoruptic, Episiltic, Protostagnic, Bathyluvic); texture – silty clay loam. Crop rotations included wheat monocrop, and winter wheat–winter oilseed rape and cereal-winter oilseed rape-faba bean sequences. Every month during the growing season, soil samples at three different depths (0–20, 20–40, and 40–60 cm) were taken and the $N–NO_3^-$ and $N–NH_4^+$ content was analyzed. The content of $N_{min.}$ in soil varied significantly among years, and about half of it was found in the upper 0–20 cm soil layer. The tillage method had little effect on $N_{min.}$ in soil; however, a trend of its higher concentrations was observed in conventional tillage compared to the reduced one. The average $N_{min.}$ content in the 0–60 cm and 0–20 cm soil layer during growing seasons was year-dependent. The least 5-year averaged amount of $N_{min.}$ in soil at the depth of 0–60 cm (54.8 kg ha^{-1} N) was determined under wheat monocrop, whereas the highest $N_{min.}$ amount (66.3 kg ha^{-1} N) was found under cereal-winter oilseed rape-faba bean rotation.
Keywords: conventional tillage, non-inversion tillage, $N_{min.}$, winter wheat.

Introduction

Farming system has changed over the past decades, which has resulted in the use of less diversified crop rotations, separation of crop production from animal farming, changes in tillage intensity, and increased use of manufactured N fertilisers (Dinnes et al., 2002; Ruža, 2013). There are several estimates, and some of them quite alarming. For example, the statement that approximately 50% of applied N fertiliser are lost from agricultural land (Tonnito et al., 2006). To reduce and minimise environmental risk, different measures that decrease nitrate leaching have been introduced in most Nordic–Baltic countries (Stalnacke et al., 2014). Nevertheless, the assessment and efficient use of all nitrogen resources are of high importance.

Nitrogen is a biologically essential element that influences soil fertility, crop growth, and yield formation. In the soil, organic nitrogen compounds dominate, while in plant nutrition, mineral nitrogen is the most important element. Mineralization of soil organic matter and the formation of plant-available mineral nitrogen (NH_4^+ and NO_3^-) are strongly influenced by environmental and anthropogenic factors such as climatic conditions, the soil physical, chemical and biological properties, vegetation type, soil management practices, and fertiliser application (Butterbach-Bahl, Gundersen, 2011).

Nowadays, farmers worldwide are adopting conservation tillage methods to reduce soil erosion, improve soil quality, increase water infiltration, and reduce the number of passes of farm equipment over their fields (Stubbs et al., 2004). However, many studies have shown an increased amount of soil mineral nitrogen after tillage operations (Watts et al., 2000; Malhi et al., 2006). Tillage disturbs the soil, places incorporated crop residues at different depths, and creates an environment for the mineralization of soil organic matter. The result is increased aerobic microbial activity in the soil due to the changes in soil structure, soil aeration and temperature regime, incorporation of fresh organic matter, and exposure of organic substances, previously protected within aggregates, to the attack by microorganisms (Stenberg et al., 1999; Rasmussen, 1999; Young, Ritz, 2000; Myrbeck et al., 2012). The effect of soil tillage on soil mineral nitrogen ($N_{min.}$) is complex – it can be influenced both by crop rotation and local soil and climatic conditions. Rice et al. (1987) found a higher nitrogen mineralization rate in ploughed soil compared to no-till soil at one site (well drained), an opposite effect at another site (poorly drained), and no significant differences between tillage systems at four other sites. Results of a field experiment (Hoffmann et al., 1996) comparing conventional tillage (ploughing to a depth of 30 cm), deep non-inversion tillage (chisel ploughing down to 30 cm), and shallow non-inversion tillage (cultivation down to 10 cm) revealed a faster mineralization rate with reduced tillage at the 0–10 cm depth compared to conventionally tilled plots. The inverse of this relationship was observed at the 10–20 cm depth, and no differences were observed in the 20–30 cm layer. It was found (Six et al., 1999; Catt et al., 2000; Coppens et al., 2007) that under favourable conditions with optimal water, oxygen and temperature regimes in the soil, decomposition can be more effective and nitrogen turnover rates faster when residues are incorporated by conventional tillage, whereas plant residues are decomposed at a lower rate when left on soil surface or in the upper layer of the soil profile in a reduced and no-till system. Some studies (Simard et al., 1994; Salinas-Garcia et al., 1997; Muruganandam et al., 2010) underline greater soil moisture, higher microbial activity, and more intensive nitrogen transformation rates throughout the growing season in reduced and no-till systems compared to mouldboard ploughing. Oorts et al. (2007) did not reveal any significant differences in $N_{min.}$ content between different tillage systems. According to Sieling et al. (1999) and Silgram & Sheperd (1999), any increase in N mineralization following cultivation is relatively short-lived, and soil mineral nitrogen measured in spring and after harvest does not usually show a consistent effect of soil tillage regime.

Soil nitrogen availability in different tillage systems is often associated with grown crops and crop sequence. Seedbed preparation when carried out close to the sowing time can contribute to N availability and supply the amount of N needed in the early phase of crop growth (Stenberg et al., 1999; Marchetti, Castelli, 2011; Myrbeck et al., 2012). In a reduced tillage system, crop yield reduction has been attributed to a low soil nitrogen supply (Lundy et al., 2015), but it can ensure equivalent or even higher yields if accompanied by an appropriate crop sequence. Reductions in yield and N availability were more evident in continuous wheat than in wheat–faba bean or wheat–berseem clover rotations (Ruisi et al., 2016). Legume-based crop rotations provide opportunity to reduce N input owing to N fixation and little or no N fertiliser application to legumes during their growth. Due to increased uptake, crop rotation can reduce soil residual nitrogen compared to monocropping (Sainju et al., 2017). The ability of legumes to fix atmospheric N results in the accumulation of N in soil; therefore, soil mineral nitrogen should be carefully managed (Marley et al., 2013; Grant et al., 2016). Deep-rooted crops scavenge deep residual soil N and increase N availability to subsequent crops (Sharifi et al., 2008). Crop residues contribute to $N_{min.}$ supply depending on its chemical composition, C/N ratio, and ease of decomposition. Residues with a low C/N ratio are expected to decompose rapidly and cause little immobilization (Thorup-Kristensen et al., 2003). Legume residues result in more efficient conversion to stable organic matter than cereals. Soil disturbance ensures a faster legume residue decomposition and more available N in soil at the end of summer for the subsequent crop (Carranca et al., 2009). In field trials with oilseed rape, peas and oats as preceding crops for winter wheat, more $N_{min.}$ at harvest time and during winter wheat growing season was ensured by winter oilseed rape and peas than by oats. When incorporated into soil, crop residues caused N immobilisation during autumn and winter, thus diminishing the risk of N leaching (Engstrom, Linden, 2009).

Results of soil mineral nitrogen dynamics vary sufficiently markedly among different soil and climatic regions, and the effect of soil tillage practices and cropping systems on local soil nitrogen supply remains unclear. However, an assessment of soil mineral nitrogen is crucial for the development of accurate fertiliser N recommendations and for minimizing environmental risk of nitrogen losses to water bodies and atmosphere (Olfs et al., 2005; Ten Berge et al., 2007; Hong et al., 2007; Rutkowska, Fotyma, 2009; Zebarth et al., 2009).

The objectives of the current study were: (i) to provide data on the seasonal and temporal variations in soil mineral nitrogen content and on N distribution in soil profile, and (ii) to identify the impact of conventional and reduced tillage and different crop sequences on soil mineral nitrogen dynamics.

Materials and methods

Site description

The research was conducted at the Study and Research Farm "Peterlauki" (56º30.85'N, 23º41.66' E, 20 m a.s.l.). The soil at the experimental field is Cambic Calcisol (Aric, Endohypocalcic, Ochric, Endoruptic, Episiltic, Protostagnic, Bathyluvic) (IUSS Working Group..., 2015). Ap horizon (0–42 cm) was silty clay loam (10% sand, 58% silt, 32% clay). At the beginning of this study, topsoil pH was 6.92±0.12 (in KCl suspension), soil organic matter was 24.0±0.1 g kg^{-1} (Tyurin's method), total nitrogen was 1.20±0.04 g kg^{-1} (Kjeldahl method), and plant available phosphorus and potassium were 124±5 mg kg^{-1} P_2O_5 and 217±12 mg kg^{-1} K_2O respectively (Egner–Riehm (DL) method). A full description of the soil profile at the experimental site is found in the literature (Karklins et al., 2018).

Experimental design and crop management

A long-term field experiment including two tillage systems – conventional tillage with moldboard ploughing at a depth of 22–24 cm (CT) and reduced tillage with shallow disking to a depth of 10 cm (RT) – was established in 2009. Tillage treatments were cropped with winter wheat (WW), winter barley (WB), winter oilseed rape (WR), and faba bean (FB). Crop rotations included wheat monocrop (Mono), winter wheat–winter oilseed rape (Rot1), and cereal–winter oilseed rape–faba bean (Rot2). In 2014, due to winter wheat damage in winter and spring, wheat (SW) was sown in all plots. The treatments were arranged in two blocks, and a split-plot design with two replicates was used for investigations; the plot size was 0.25 ha. The cultivation and tillage treatments were performed with commercial farm equipment. After harvesting, crop residues (straw) were incorporated into the soil. Annual nitrogen, phosphorus and potassium application rates were based on soil test recommendations for the planned crop yield level (Karklins, Ruza, 2013). Crops grown and N fertiliser applied are presented in Table 1. Crop sequence during the current experiment (2012–2016) is shown in Table 2.

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Table 1. Agrotechnics of crops grown

Year	Crop	Date of tillage	Fertiliser, kg ha^{-1} N	
			Autumn	Spring
2011/2012	Winter wheat 'Zentos'	29.08.2011	17.5	129
	Winter barley 'Carola'	29.08.2011	17.5	129
2012/2013	Winter wheat 'Zentos'	15.–16.08.2012	21	150
	Winter oilseed rape 'Visbi'	15.–16.08.2012	21	160
2013/2014	Winter wheat 'Zentos'	04.09.2013	30	–
	Spring wheat 'Taifun'	19.04.2014	–	119
2014/2015	Winter wheat 'Zentos'	16.09.2014	14	153
	Faba bean 'Laura'	20.10.2014	–	37.5
2015/2016	Winter wheat 'Zentos'	14.–16.09.2015	14	170
	Winter oilseed rape 'Visbi'	14.–15.08.2015	14	170

Table 2. Crop sequence during the experiment (2012–2016)

Crop rotation	2012	2013	2014	2015	2016
Mono	WW	WW	WW/SW	WW	WW
Rot1	WW	WR	WW/SW	WW	WR
Rot2	WB	WR	WW/SW	FB	WW

Soil mineral nitrogen measurement

Soil mineral nitrogen was monitored from April 2012 to August 2016. Soil sampling was performed throughout the growing period from the reestablishment of plant growth in early spring (March/April) until late autumn when the temperature fell below 0°C, usually in the last decade of each month, at three different depths (0–20, 20–40, and 40–60 cm) and in three replications. Soil samples were deep-frozen (-20°C) immediately after sampling. The nitrate ($N–NO_3^-$) and ammonium ($N–NH_4^+$) nitrogen concentrations in soil samples were tested according to the LVS ISO 14256–2 standard methodology (KCl extraction). Taking into consideration soil moisture and bulk density, the soil mineral nitrogen pool was calculated.

Statistical analysis

Analysis of variance (ANOVA) was used for soil mineral nitrogen data processing. Treatment means were compared using Fisher's least significant difference (LSD) test at $P<0.05$. The effect of tillage was evaluated by comparing the averages of three crop rotations; the effect of crop rotation was evaluated comparing the averages of two tillage methods. Error bars in Fig. 1 indicate ± of the standard error.

Weather conditions

The air temperature and precipitation data was obtained from a meteorological station located 20 km from the experimental field. During the experiment, average temperatures were near the long-term averages. Amounts of rainfall during the growing period differed among months and seasons (Table 2). In 2012, the amount of precipitation exceeded the long-term average by 135%, while in 2015, the sum of precipitation in April–August was only 69% from the long-term averages. Water deficit was most evident in June and August of 2015. Excessive moisture was more typical in July 2012 and May 2013.

Table 3. Amounts of precipitation, and long-term averages, mm

Months	2012	2013	2014	2015	2016	Long-term average
April	65	39	35	57	54	39
May	38	92	49	42	25	43
June	58	38	67	16	60	52
July	139	40	47	74	95	73
August	78	89	113	6	61	74
Total	378	298	311	195	295	281

Results and discussion

During the experiment (2012–2016), significant differences ($P<0.05$) in $N_{min.}$ content in the 0–60 cm and 0–20 cm soil layers were detected among the years. The least averaged $N_{min.}$ amount in the 0–60 cm layer in the sampling period (March–November) was found in 2012 – 39.0 kg ha^{-1} N. The highest $N_{min.}$ content – 62.7 kg ha^{-1} N – was found in 2014 and 2016, while in 2013 and 2015, the amounts of $N_{min.}$ were similar ($P>0.05$) – 47.4 and 52.6 kg ha^{-1} N respectively (Table 4). Large variations in $N_{min.}$ concentrations among seasons have been reported also by other authors and attributed to climate conditions, date of sampling, and $N_{min.}$ spatial distribution depending

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on site heterogeneity, the soil and crop management practices, and other factors (Astatkie et al., 2001; Giebel et al., 2006; Sainju et al., 2017). In our study, the highest averaged $N_{min.}$ content in 2014 might have been inspired by the mineralization of easily decomposable crop residues after incorporation of winter wheat residues (that have been left after winter wheat damage during winter) in spring. Those residues were incorporated during seedbed preparation for spring wheat, which made some nitrogen-rich material inputs into the soil. The high $N_{min.}$ content in 2016 might be the result of the low efficiency of N use in 2015 due to the drought in some periods of crop growth.

Table 4. The average $N_{min.}$ content in the 0–60 cm and 0–20 cm soil layers, kg ha^{-1} N

Year	Early spring (March–April)	Intensive growth (April–July)	At harvest (August)	Late autumn (November)	Sampling period (March–November)
0–60 cm depth					
2012	n.d.	43.2a	34.1a	26.7a	39.0a
2013	29.3a*	58.3a	27.6a	34.6b	47.4b
2014	47.6b	98.4b	25.5a	37.7b	62.7c
2015	33.8a	59.7a	47.3b	41.9c	52.6b
2016	23.7a	79.3ab	35.1a	n.d.	62.7c
2012/2016	36.5	67.8	36.3	35.2	52.9
0–20 cm depth					
2012	n.d.	26.7a	19.1a	12.9a	21.9a
2013	11.6a	35.8b	14.6a	16.0a	25.1a
2014	20.9b	54.9c	14.6a	16.5a	33.4b
2015	13.5a	24.0a	19.3a	18.4ab	21.7a
2016	9.5a	38.0b	14.3a	n.d.	25.4a
2012/2016	18.0	35.9	18.0	15.9	25.5

* Different letters in the same column denote significant (P<0.05) differences in F test.

Over the five-year investigation period, $N_{min.}$ content was highly variable among sampling dates and treatments, which was in agreement with the results obtained by other researchers (Sippola, 2000; Giacomini et al., 2010; Marcheti, Castelli, 2011). In the first soil sampling period (shortly after the reestablishment of plant growth in March–April), the average amount of $N_{min.}$ content in the 0–60 cm soil layer usually was low: 23.7–33.8 kg ha^{-1} N (Table 2). A significantly higher (P<0.05) $N_{min.}$ amount (47.6 kg ha^{-1} N) was measured only in 2014, when due to poor overwintering of winter wheat, all plots in spring were sown with spring barley. After N fertiliser application (April–May), a substantial peak in N concentrations (with large variations in measurements) was observed.Thus, at May sampling date, an average $N_{min.}$ content of 95.3 kg ha^{-1} N was reached within the range of 27.8 to 185.4 kg ha^{-1} N. During the period of intensive crop growth, the average $N_{min.}$ content in the 0–60 and 0–20 cm soil layers was about two to three times higher than that in early spring. However, total $N_{min.}$ content dropped rapidly to the minimum because of an intensive uptake of nitrogen by crops. Later in the period of crop harvest and throughout autumn, variations in $N_{min.}$ content diminished and the average amount of $N_{min.}$ was slightly below that in early spring. Some authors (Kayser et al., 2008; Sosulski, Mercik, 2011) reported an increase in $N_{min.}$ concentration after crop harvest because the uptake of nitrogen by crops had ceased. In our experiment, winter crops (winter wheat and winter oilseed rape) were sown soon after harvest, which utilized residual $N_{min.}$ during autumn period.

Previous studies in different soil and climatic regions had revealed that the disturbance of surface soil with conventional, reduced or no tillage practices creates both different conditions for soil organic matter mineralization and different levels of available mineral nitrogen in soil. Some researchers found higher $N_{min.}$ concentrations after deep-soil cultivation (Drinkwater et al., 2000; Henke et al., 2008; Franzluebbers, Stuedemann, 2013; Ruisi et al., 2016), whereas others underlined significant $N_{min.}$ accumulations in the upper soil layer after reduced tillage (Soon et al., 2001; Montemurro, Maiorana, 2014). There are experiments where no significant differences in $N_{min.}$ content between conventional and reduced tillage were detected (Hoffmann et al., 1996; Sieling et al., 1999; Oorts et al., 2007). In the present study, tillage methods had minor effect on $N_{min.}$ content in the soil (Fig. 1). Averaged over all sampling dates and years, $N_{min.}$ content in the soil depth of 0–60 cm (0–20 cm) was 51.9 kg ha^{-1} (25.7 kg ha^{-1}) in plots of conventional tillage, and 50.0 kg ha^{-1} (25.3 kg ha^{-1}) in plots of reduced tillage. No significant differences in the 5-year average $N_{min.}$ concentrations were found between CT and RT plots for soil sampling dates as well. However, in several seasons (2012, 2013, and 2016), inconsistent significant differences between N_{min}. in CT and RT treatments were noticed. Thus, in 2012 and 2016, the content of $N_{min.}$ was by 9.6 and 14.2 kg ha^{-1} N higher (P<0.05), respectively, in plots of conventional tillage, while in 2013, the opposite was observed – the level of $N_{min.}$ was by 13.6 kg ha^{-1} higher (P<0.05) in reduced tillage plots. Temporal variations in $N_{min.}$ content in soil over the period of March–November were similar for both tillage methods. As emphasized by Stubbs et al. (2004), the effect of tillage appears after a period of time when a new equilibrium in soil properties has been achieved. Our experiment suggests that a 5-year period is not sufficient for attaining such equilibrium.

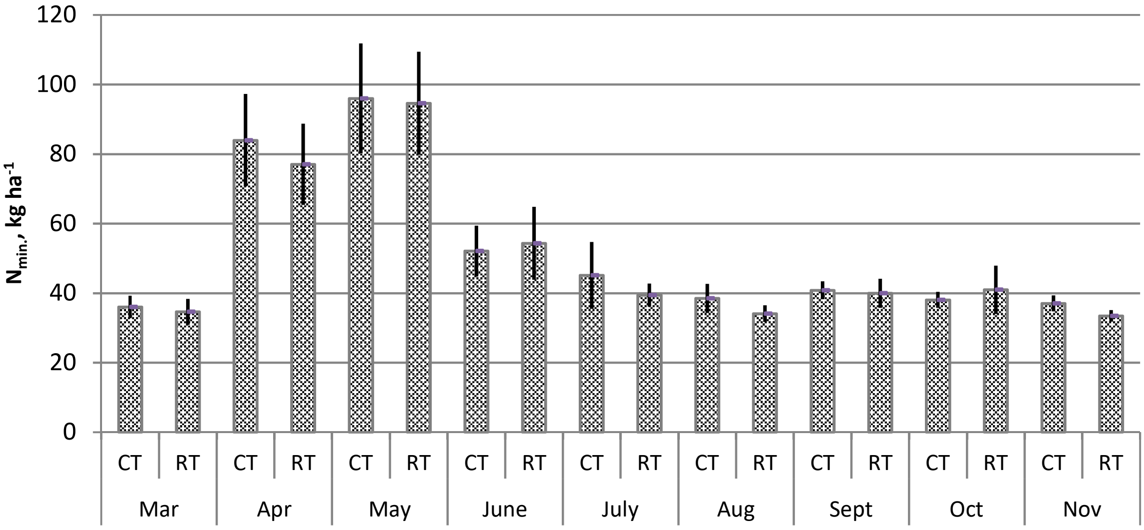

Figure 1. Average $N_{min.}$ content in the 0–60 cm soil layer in plots of conventional tillage (CT) and reduced tillage (RT). (Vertical bars represent the standard error)

In the experimental plots, plant-available nitrogen was not evenly distributed in the soil profile. About half of the total $N_{min.}$ content in the soil 0–60 cm layer was located in the 0–20 cm surface horizon (Fig. 2). The proportion of $N_{min.}$ in the 0–20 cm layer fluctuated during sampling periods and among treatments. In early spring, about 39% of total $N_{min.}$ were measured at the 0–20 cm depth in CT plots and 44% were measured in RT plots. After N fertiliser application, the proportion of $N_{min.}$ in the surface layer increased up to 60% of the total N content, then decreased gradually in all plots, and in late autumn, the proportion of $N_{min.}$ at the 0–20 cm depth was slightly higher than in early spring. Results of autumn sampling dates showed a consistent effect of soil tillage. The content of $N_{min.}$ in RT plots was higher than in CT plots. The increase in $N_{min.}$ concentration in the upper horizon of shallow tillage treatment might be caused by more favourable conditions for mineralisation of post-harvest residues (Sosulski, Mercik, 2011). Soil mineral nitrogen content in a deeper soil layer (40–60 cm) was considerably lower than that in the upper layer, i.e., on average, 15% of the total $N_{min.}$ amount in the 0–60 cm profile. A higher proportion of mineral nitrogen in deeper soil horizons was more typical for early spring and late autumn sampling dates. After soil tillage and seedbed preparation in autumn, the amount of $N_{min.}$ in the 40–60 cm layer was higher in plots of conventional tillage compared to reduced tillage plots. Comparison of $N_{min.}$ distribution in soil profiles in late autumn and early spring confirmed a downward movement of nitrates during the autumn–winter period because less nitrogen in the 0–20 cm and 20–40 cm layers and more nitrogen at the 40–60 cm depth were measured in soil samples in spring. Temporal variations in and proportions of $N_{min.}$ among soil layers in our study were comparable to those found in some other experiments in the literature (Rutkowska, Fotyma, 2011; Myrbeck et al., 2012; Kolodziejczyk, 2013; Arbačiauskas et al., 2014).

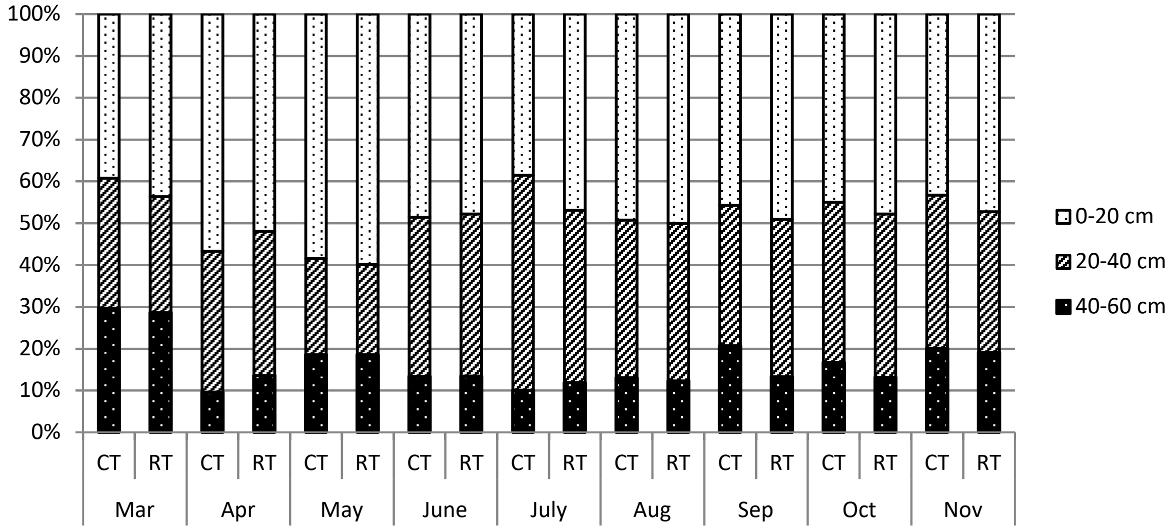

Figure 2. Proportion of $N_{min.}$ content in the 0–20 cm, 20–40 cm, and 40–60 cm layers of soil profile

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Similarly to the findings reported in other studies (Möller, Stinner, 2009; Plaza et al., 2012), nitrate nitrogen dominated in soil throughout the whole period of our experiment, although the proportion between the nitrate and ammonium nitrogen contents varied among years, samplings, and treatments. Averaged over all treatments, a significantly higher (P<0.05) nitrate-N content in the soil 0–20 cm layer of trial plots was found in 2013 and 2014, when the most favourable conditions for nitrification were observed, while a higher ammonium nitrogen concentration was detected in 2012 and 2016. The effect of tillage on the content of mineral nitrogen forms was strongly dependent on the year (Table 5). Nitrate-N amount in the 0–20 cm layer was significantly higher (P<0.05) in conventional tillage plots than in the reduced ones in 2012 and 2016. The trend was in agreement with the results of Franzluebbers & Stuedemann (2013), who attributed this to better mineralization of organic matter after soil ploughing. However, in our experiment, the reverse was true for nitrate-N in 2013, but difference between tillage methods was inconsiderable in 2014 and 2015. The average (2012–2016) nitrate-N content in the 0–20 cm soil layer was 16.2 kg ha^{-1} under conventional tillage treatment and 16.8 kg ha^{-1} under the reduced one. Compared to reduced tillage plots, larger ammonium-N concentrations were noted in conventional tillage plots in three out of the five years of our experiment, but differences were not statistically significant for a 5-year period. The average (2012–2016) ammonium-N content in CT and RT plots was 8.8 and 7.6 kg ha^{-1} N, respectively.

Table 5. Content of mineral nitrogen in the 0–20 cm soil layer depending on soil tillage methods (average in March–November), kg ha^{-1} N

	2012	2013	2014	2015	2016	Total
Nitrate-N						
CT	16.0	15.1	24.5	13.5	16.1	16.2
RT	12.3	22.3	24.2	13.0	10.9	16.8
LSD_{05}	3.0	5.3	5.6	4.8	3.1	3.3
P	0.017	0.009	0.911	0.831	0.002	0.716
Ammonium-N						
CT	9.1	6.4	10.8	6.1	11.7	8.8
RT	7.0	7.9	7.3	6.6	9.4	7.6
LSD_{05}	2.6	2.8	3.0	2.7	1.5	1.6
P	0.107	0.287	0.021	0.677	0.004	0.152

Temporal variations in the nitrate and ammonium nitrogen content in soil surface horizons over sampling dates had a similar pattern in conventional and reduced tillage plots (Fig. 3). No significant differences in nitrate-N content were obtained between tillage treatments at sampling dates. The content of nitrate-N in conventional and reduced tillage plots increased significantly after N fertiliser application in spring (April–May). In April, 5 kg ha^{-1} more (P>0.05) nitrate-N was measured in ploughed soil compared to reduced tillage plots. However, during the next sampling (in May), an identical nitrate-N amount was determined in the soil of both tillage treatments, which indicated a greater nitrification intensity under reduced tillage. After the increase in nitrate-N amount since early spring – by 26.4 and 27.7 kg ha^{-1} N in conventional and reduced tillage plots respectively –, the nitrate concentration decreased sharply during the next two-month period. At harvest time, the amount of soil nitrate-N was equal to that in early spring. After harvest, a slight increase (P>0.05) in nitrate concentration in ploughed soil compared to shallow tillage treatment was observed. In late autumn, variations in nitrate nitrogen content in the 0–20 cm soil layer were insufficient.

Variations in ammonium-N content in the soil 0–20 cm horizon under conventional and reduced tillage treatments during sampling period were similar to those in nitrate-N content, although an exception was noted in the sampling period of May (Fig. 3). Unlike nitrate-N, further increase in ammonium-N content during May did not occur. The content of ammonium-N in reduced tillage treatment plots remained at a lower (by about 7 kg ha^{-1} N) level than that in conventional tillage plots, which could be explained by a higher nitrification intensity of ammonium-N in soil under reduced tillage. In autumn, after sampling in July, a certain increase in ammonium-N content was observed. This might be due to organic matter mineralization caused by soil tillage operations before seeding winter crops. In late autumn, ammonium-N content at the 0–20 cm soil depth in both tillage treatment plots was 3 kg ha^{-1} N higher than at the first sampling in March. However, the differences were not statistically proved because of the wide variations in ammonium nitrogen concentrations among years in that period.

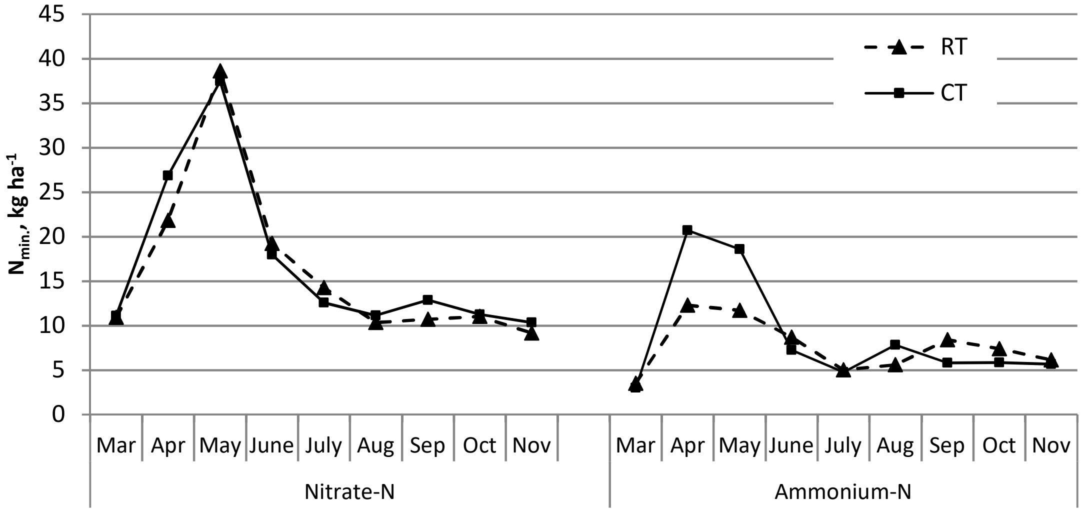

Figure 3. Variations in the nitrate and ammonium nitrogen content in the 0–20 cm soil layer under conventional (CT) and reduced (RT) tillage treatments (average in 2012–2016)

A sufficient supply of available soil nitrogen is important during April–August for all crops grown. In this period, mineral nitrogen content in the soil 0–60 cm and 0–20 cm layer was year-dependent (Table 6). Thus, under wheat monocrop, $N_{min.}$ content was significantly higher in 2016 compared to 2012, 2013, and 2015. Under winter oilseed rape, $N_{min.}$ content was 53.1 kg ha^{-1} N in 2013, and 81.9 kg ha^{-1} N in 2016, whereas under previous crop, $N_{min.}$ content was 43.9 and 42.2 kg ha^{-1} N in 2012 and 2015, respectively. A significant year-to-year variation in $N_{min.}$ amount under different crops in a temperate climate as a result of diverse conditions for mineralization has been reported (Sieling et al., 1999; Gruber et al., 2011). In the 0–60 cm soil layer, the least 5-year averaged amount of $N_{min.}$ (54.8 kg ha^{-1} N) was determined under wheat monocrop, whereas the highest averaged $N_{min.}$ amount (66.3 kg ha^{-1} N) was detected under cereal–winter oilseed rape–faba bean rotation. However, differences in average (2012–2016) mineral nitrogen concentrations among crop sequences were not significant (P>0.05).

Table 6. Average $N_{min.}$ content during crop growth (April–August) in the 0–60 cm soil layer, and the nitrate and ammonium nitrogen content in the 0–20 cm soil layer, kg ha^{-1} N

Crop rotation	Year	Crop	$N_{min.}$ 0–60 cm	NO_3–N 0–20 cm	NH_4–N 0–20 cm
Mono	2012	winter wheat	46.5a	15.9b	12.6b
	2013	winter wheat	43.0a	20.3bc	5.0a
	2014	spring wheat	66.8b	26.6c	8.1a
	2015	winter wheat	47.0a	9.5a	6.3a
	2016	winter wheat	70.8b	15.9b	15.5b
Rot1	2012	winter wheat	43.9a	17.8b	9.4ab
	2013	winter oilseed rape	53.1a	28.1c	6.3a
	2014	spring wheat	95.3b	42.2d	13.8b
	2015	winter wheat	42.2a	9.5a	4.4a
	2016	winter oilseed rape	81.9b	21.4b	13.1b
Rot2	2012	winter barley	40.6a	13.9a	10.9a
	2013	winter oilseed rape	60.3a	24.8b	10.2a
	2014	spring wheat	89.3b	36.2c	13.7a
	2015	field bean	82.5b	21.5b	9.7a
	2016	winter wheat	58.8a	11.9a	14.6a
Crop sequences (average in 2012–2016)					
Mono			54.8	17.6	9.5
Rot1			63.3	23.8	9.4
Rot2			66.3	21.7	11.8
		LSD_{05}	15.9	7.1	3.6
		P	0.333	0.220	0.333

* Different letters in the same column denote significant (P<0.05) differences in F test.

Nitrate-N concentration at the 0–20 cm soil depth was more dependent on the crops grown. The trend observed during the 5-year crop rotation period revealed a higher nitrate nitrogen amount under winter oilseed rape and faba bean, and a smaller nitrate amount under winter wheat and winter barley. The results suggest that higher concentrations of nitrate nitrogen under spring wheat were not due to the grown crop but due to specific soil conditions after the incorporation of a poorly overwintered preceding crop. The average 5-year nitrate-N amount was 17.6 kg ha^{-1} under wheat monocrop, 23.8 kg ha^{-1} under winter wheat–oilseed rape rotation, and 21.7 kg ha^{-1} under cereal–winter oilseed rape–faba bean rotation. However, those differences were not significant at a 95% probability level, because nitrate-N measurements varied substantially among the years. Thus, soil nitrate-N content was significantly lower ($P<0.001$) in continuous wheat compared to Rot2 in 2014 and 2015 and Rot1 in 2014. In contrast, Sainju et al. (2017) reported a larger nitrate-N and ammonium-N content with continuous durum wheat in comparison to crop rotation, attributing this to diminished yields and, consequently, less N uptake by the monocrop. A higher average soil nitrate-N content under winter wheat–winter oilseed rape rotation compared to that under cereal–winter oilseed rape–faba bean rotation in our experiment was in agreement with the findings of Malhi et al. (2002), namely, cropping systems with a low diversity and high fertiliser inputs resulted in a greater soil nitrate-N accumulation than cropping systems with a high diversity and reduced or organic fertiliser inputs.

Ammonium-N content in soil upper 0–20 cm layer varied among years with a significantly higher ($P<0.001$) content: under continuous wheat – in 2012 and 2016, and under winter wheat–winter oilseed rape rotation – in 2014 and 2016; whereas under cereal–winter oilseed rape–faba bean rotation, differences among years were not significant. A higher ammonium-N content could be a result of a low nitrification rate under specific agroclimatic conditions in the growing period (Corbeels et al., 1999). Averaged over 5-year crop rotation period, the ammonium-N content at the 0–20 cm soil depth was higher ($P>0.05$) under cereal–winter oilseed rape–faba bean rotation and did not differ between the monocrop wheat and winter wheat–winter oilseed rape sequence.

Temporal variations in $N_{min.}$ content throughout the sampling period did not show significant differences between the three cropping systems (Fig. 4). According to Marcheti & Castelli (2011), for all crops, nitrogen uptake is different in different growing phases. This can explain the differences observed among $N_{min.}$ contents in soil among winter wheat, winter oilseed rape and spring wheat in the April–May period. At the first sampling time, $N_{min.}$ content in the 0–60 cm soil layer ranged between 30.1 and 47.6 kg ha^{-1} N, with a higher value for spring wheat due to specific conditions after damaged winter crop incorporation in early spring of 2014. After fertiliser N application to winter wheat and winter oilseed rape, as well as seedbed preparation for spring wheat in 2014, $N_{min.}$ content increased extensively. While the increase in $N_{min.}$ concentration under winter wheat and oilseed rape was related to fertiliser application, a certain effect of N mineralization was observed under spring wheat. The highest $N_{min.}$ content under winter wheat was observed in April, but under winter oilseed rape and spring wheat – a month later. At these sampling dates, spring wheat was still in early growth phase, when uptake was slow, but winter crops were already in full development. The soil and fertiliser N resources were depleted until July sampling date, when $N_{min.}$ content in soil under all three crops dropped to the initial (March) level. Under spring wheat, a reduction in $N_{min.}$ resources was detected also in August. Variations in $N_{min.}$ concentration after crop harvest were due to tillage operations carried out at different dates.

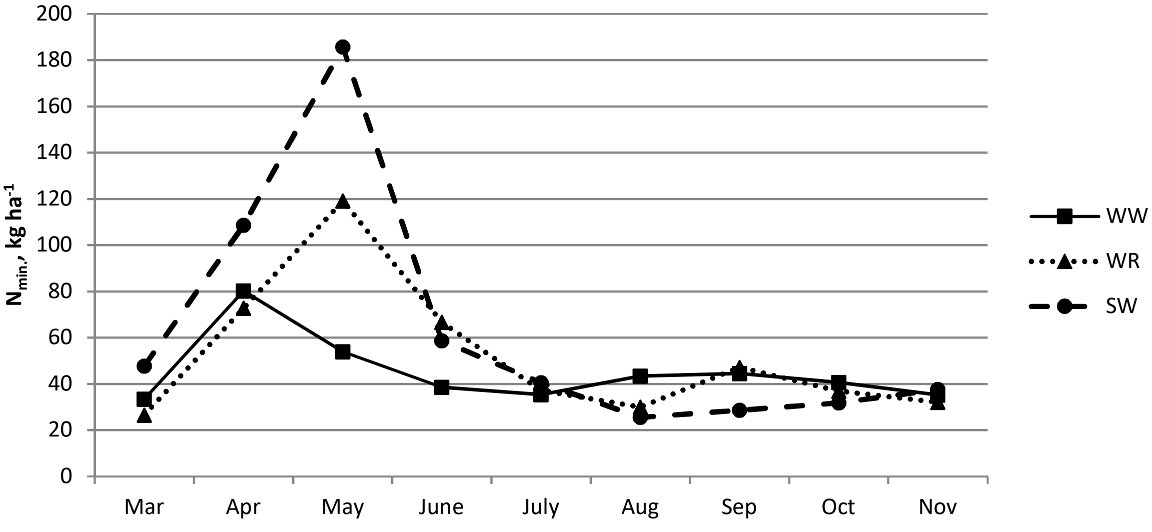

Figure 4. Variations in $N_{min.}$ content at the 0–60 cm depth under different crops (average for all treatments)

Due to large variations in measurements among years, the impact of crops grown in plots of conventional and reduced tillage on $N_{min.}$ content was negligible. A significant difference among crop rotations was revealed only at one sampling date (early spring) when $N_{min.}$ content in soil under continuous wheat was substantially lower in comparison with two other crop rotations. Nevertheless, the trend was typical also for further samplings and the 5-year average $N_{min.}$ content. The average amount of $N_{min.}$ at the 0–60 cm depth for continuous wheat grown after soil ploughing and after shallow disking was 48.9 and 46.1 kg ha^{-1} N, respectively. Under crop sequence of winter wheat–winter oilseed rape, $N_{min.}$ content was to some extent higher (54.5 and 52.0 kg ha^{-1} N respectively), but similar to that under cereal–winter oilseed rape–faba bean crop rotation: 52.4 and 51.3 kg ha^{-1} N under conventional tillage and reduced tillage, respectively. Although differences in $N_{min.}$ content between tillage treatments were not significant, they were in agreement with those reported by Ruisi et al. (2016) that reduction in soil disturbance leads to a lower $N_{min.}$ content in continuous wheat compared to plots under wheat–legume crop rotation.

Temporal variations in nitrate-N concentration during soil sampling period (March–November) were similar for the three rotations. A significant (P<0.001) increase in nitrate-N concentration in April and May compared to that in early spring (March), followed by sharp decrease in June–July, was characteristic on the occasion of both tillage treatments – conventional and reduced (Fig. 5). The highest increase in soil nitrate-N content at the 0–20 cm soil depth after fertiliser N application in spring was obtained under wheat–winter oilseed rape rotation, where average total annual fertiliser rate was 165.5 kg ha^{-1} N. Nitrate-N content reached on average 43.7 kg ha^{-1} and 47.0 kg ha^{-1} N in plots under conventional and reduced tillage treatment, respectively. In wheat monocrop plots, the increase in nitrate concentration was by 13.6–15.5 kg ha^{-1} N lower (P>0.05) than that in wheat–winter oilseed rape plots, though wheat monocrop annually received equal amounts of fertiliser (163.5 kg ha^{-1} N). Under the crop rotation of cereal–winter oilseed rape–faba bean, soil nitrate-N content in May sampling exceeded that under wheat monocrop, although the average annual fertiliser N rate during rotation was only 139.6 kg ha^{-1} N.

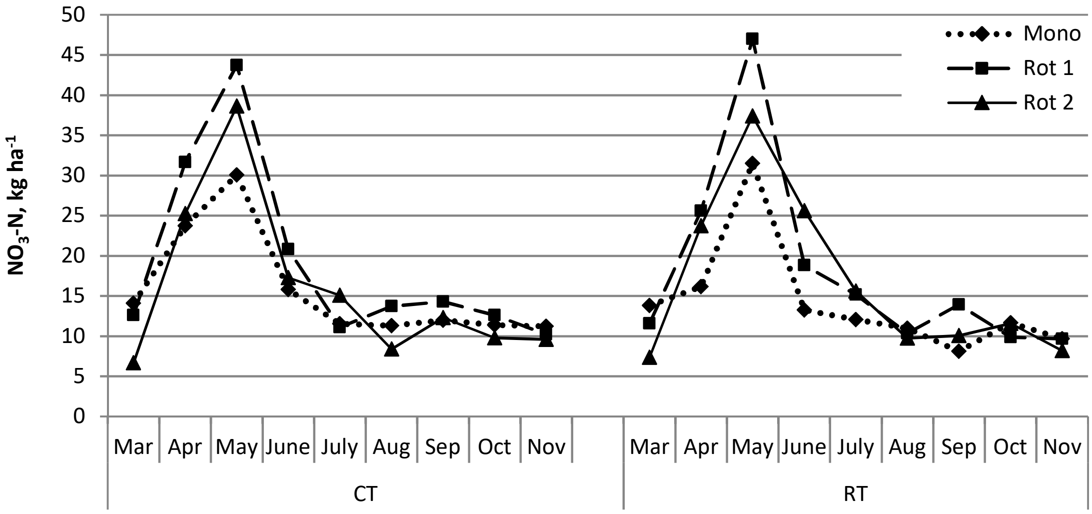

Figure 5. Variations in nitrate-N content at the 0–20 cm soil layer under the continuous wheat (Mono), winter wheat–winter oilseed rape (Rot1), and cereal–winter oilseed rape–field bean (Rot2) rotations (5-year averages)

The pattern of nitrate-N concentration decrease in the course of N uptake under the rotation of cereal–winter oilseed rape–faba bean differs compared to that under two other rotations. After the peak in concentration variations in May, the amount of nitrate-N decreased gradually and reached its lowest level in August; while under wheat monocrop and winter wheat–winter oilseed rape rotation, nitrate resources were exhausted in a shorter time period. Soil nitrate-N measurements under faba bean revealed a somewhat different pattern of nitrate concentration variation during the growing period. The highest concentration of nitrate-N at the soil 0–20 cm depth was achieved in June: 33.0 kg ha^{-1} N under conventional tillage treatment, and 44.8 kg ha^{-1} N under reduced tillage treatment. After that, nitrate-N content in soil remained at the 15–25 kg ha^{-1} N level until November, which was twofold higher than under other crops. Results of studies in Germany suggested that faba bean derived more than 90% of its nitrogen from dinitrogen biological fixation, therefore the depletion of soil nitrogen resources was low (Hauggaard-Nielsen et al., 2009); however, after grain legume harvest, a very small amount of N-rhizodeposition was found in the mineral nitrogen fraction. The recovery in wheat and rape constituted about 50% of the residue-derived nitrogen that was produced by mobilisation of residue N temporarily immobilised in the microbial biomass (Mayer et al., 2003).

Under all crop rotations at harvest and during tillage operations in autumn, changes in soil nitrate concentration were statistically insignificant. However, the increase in nitrate-N concentration in soil after the harvest of winter oilseed rape was observed under winter wheat–winter oilseed rape rotation in plots of conventional and reduced tillage, which is in agreement with Sieling et al. (1999). After the post-crop winter wheat establishment in autumn, the content of nitrate-N decreased; in November sampling, it was at the same level as in early spring. As reported by Sieling & Kage (2010), a high residual nitrogen content after oilseed rape harvest occurred when fertiliser rates exceeded 200 kg ha^{-1} N. In our experiment, fertiliser rate under winter oilseed rape was 181–184 kg ha^{-1} N, which was optimal for the obtained yield level.

Variations in ammonium-N concentration during $N_{min.}$ monitoring period differed from those in nitrate-N concentration. Differences in N dynamics were observed between tillage treatments and sampling dates (Fig. 6).

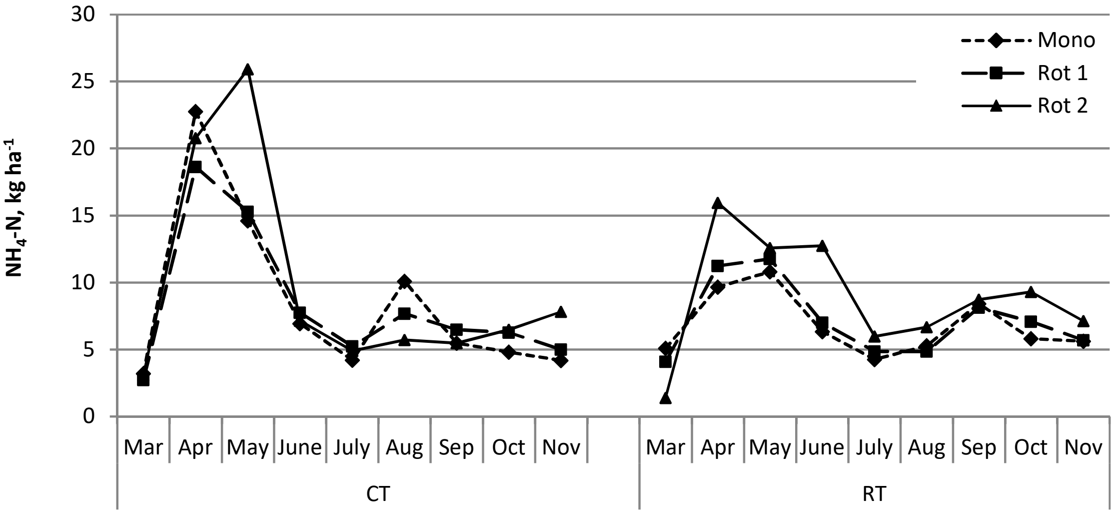

Figure 6. Variations in ammonium-N content in the 0–20 cm soil layer under the continuous wheat (Mono), winter wheat–winter oilseed rape (Rot1) and cereal–winter oilseed rape–faba bean (Rot2) rotations (5-year averages)

During spring–summer period, ammonium-N in soil under conventional tillage was detected about twice as much as under reduced tillage treatment, which might be the result of a higher mineralisation rate under specific physical conditions in ploughed soil. In two rotations – continuous wheat and winter wheat–winter oilseed rape, changes in ammonium-N concentration were comparable, whereas the rotation that included faba bean showed certain dissimilarity. The crop sequence of winter barley–winter oilseed rape–spring wheat–faba bean–winter wheat ensured a higher ammonium-N content in the 0–20 cm soil layer for a longer time of an intensive plant growth period. In late autumn, also more ammonium–N was produced in soil under that rotation; however, differences among the three rotations were not significant.

Conclusions

The content of mineral nitrogen in soil varied significantly among the investigation years. In early spring, the amount of $N_{min.}$ in the 0–60 cm soil layer ranged between 23.7 and 47.6 kg ha^{-1} N. After fertiliser application, $N_{min.}$ content in soil increased rapidly. At harvest time, the content of $N_{min.}$ was at the same level as in early spring. No significant increase in mineral nitrogen content in soil from harvest time until late autumn was noted. About half of $N_{min.}$ was located in the soil upper 0–20 cm layer. The tillage method had little effect on plant available nitrogen in soil. However, the trend of a higher amount of $N_{min.}$ and its forms (nitrate-N and ammonium-N) was observed under conventional tillage than under reduced tillage treatment. Nitrate-N dominated in soil throughout the whole period of the experiment; however, the proportion between both the nitrate nitrogen and ammonium nitrogen content varied among years, samplings, and treatments. Temporal variations in the nitrate and ammonium nitrogen content in soil surface horizon over sampling dates had a similar pattern in conventional and reduced tillage plots. In April–August, the average mineral nitrogen content in the 0–60 and 0–20 cm soil layer under grown crops was year-dependent. At the depth of 0–60 cm, the least 5-year averaged amount of $N_{min.}$ (54.8 kg ha^{-1} N) in soil was determined under wheat monocrop, whereas the highest averaged $N_{min.}$ amount (66.3 kg ha^{-1} N) was detected under cereal–winter oilseed rape–faba bean rotation. The increase in nitrate-N concentration in soil after the harvest of winter oilseed rape was observed under winter wheat–winter oilseed rape rotation in plots of both conventional and reduced tillage treatments. After the establishment of post-crop winter wheat in autumn, the content of nitrate-N decreased, and in November sampling, it was at the same level as in early spring.

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