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DISTRIBUTION OF MINERAL NITROGEN IN SOIL IN RELATION TO RISK OF NITRATE LEACHING IN FARMS WITH IRRIGATED VEGETABLES AND EARLY POTATOES

Jan HABERLE*, Pavel SVOBODA, Tomáš ŠIMON, Gabriela KUREŠOVÁ, Barbora HENZLOVÁ, Jan KLÍR
Crop Research Institute (VÚRV)
Drnovská 507, 16106, Praha, Czech Republic

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ABSTRACT

Vegetable production may be the source of excessive residual nitrate that is prone to leaching to waters. To ascertain the risk of nitrate leaching in water collection area, the content of soil mineral nitrogen (N_{min} = N-NO_3^- + N-NH_4^+) down to 120 cm depth was monitored in the years 2013–2016 on vegetable farms along lower Jizera river (in the Czech Republic). The risk of nitrate leaching below 30, 60, 90 and 120 cm during winter period was simulated with a simple model. The depths represent the limits of effective root depth and N depletion of groups of vegetables and field crops. The average autumn mineral nitrogen content in the fields, during experimental years, ranged from 101 kg to 134 kg N·ha^{-1} in the 0–120 cm soil layer, 85 to 92% of which was in the form of nitrate. The calculated leaching of nitrate from the topsoil (0–30 cm) and shallow subsoil (0–60 cm) ranged from 27 to 41%, and from 7 to 14% of autumn content, respectively. The risk of leaching below 60 cm and 90 cm was near to none during the experimental years due to the exceptionally low precipitation. High nitrate content in subsoil layers below 60 cm constitutes risk of leaching and water pollution due to shallow root systems of many vegetables and potatoes in seasons with normal weather and higher water percolation.

Keywords: losses, nitrogen depletion, root depth, soil water capacity, subsoil

INTRODUCTION

Water pollution from agriculture is globally perceived as an acute problem of environment. Residual soil mineral nitrogen from the fertilization of crops is mostly present in the form of nitrate, which is prone to leaching and may pollute surface and ground waters. Mineral nitrogen is found in farm soils (Buczko et al. 2010; Haberle et al. 2009; Lawniczak et al. 2016). Many vegetables and early potatoes demand great amounts of readily available water and nitrogen in the soil due to their shallow root system and lower absorption capacity (Neeteson et al. 1999; Neeteson & Carton 2001; Cameira & Mota 2017). The residues decompose quickly due to their structure and chemical composition, and contribute to nitrate prone to leaching during winter and spring (Whitmore 1996; Neeteson & Carton 2001). The risk is further increased by the use of irrigation, which may contribute to soil water saturation and percolation if not used according to soil water capacity, weather conditions, crop water demand, and root depletion zone (Wu et al. 2005; Cameira & Mota 2017). The factors contributing to the risk of leaching are more or less integrated into the nitrogen indexes (Wu et al. 2005; Delgado et al. 2007; Buczko et al. 2010).

The leaching of nitrates is governed by water percolating from the saturated top layers rich in mineral and organic materials. A simplified approach is satisfactory for the period between late autumn and early spring with low evapotranspiration; therefore, residual N_{min} or nitrate contents before winter are widely used as an indicator of leaching potential (Geypens et al. 2005). In short, effective

*Corresponding author:
e-mail: haberle@vurv.cz

precipitation, soil nitrate and water contents, as well as their distribution at the onset of winter are the main inputs for the estimation of nitrate leaching during this period (Burns 1976; Buczko et al. 2010). While many studies concentrated on leaching during growth due to high or inadequate irrigation and nitrogen rates (Li et al. 2017; Marchi et al. 2016), the presented monitoring of soil mineral N content aims at risk of leaching during period without crop cover, low temperatures and evapotranspiration. The between season period and early spring usually show the most intensive nitrate leaching under mild climate conditions in the Czech Republic.

The monitoring of soil N_{min} content was performed along the lower part of Jizera river – the right inflow of Labe (Elbe) river (Fig. 1). The region is used for vegetable production under irrigation. A large proportion of the soil, 35% and more in some fields, is devoted to early potatoes, partially grown for several weeks under plastic sheets to accelerate growth and avoid damage from spring frost.

The region also serves as an important source of water; about 27% of Prague's drinking water comes from the Káraný water works. The most ample source of water here is bank infiltration (at about 600 liter per second). Water is extracted by over six hundred bore wells fed by water seeping from the river, the percolation from near and distant fields, and also from farther sources with water having accumulated over previous years (Bruthans et al. 2019). The farm activities are regulated to some extent in a narrow belt along the lines of wells, but the growing of irrigated vegetables and potatoes is not prevented. The region also falls under delimited vulnerable zones, the measures have just recently included the limits on nitrogen rates for vegetables that might be controlled and sanctioned. Evidently, a set of best management practices must be introduced to minimize nitrate leaching (Hartz 2006; Geypens et al. 2005; DEFRA 2010). To harmonize the goals of both growers and the requirements for water quality, more data on the behaviour of nitrogen in the specific crop system is needed.

Objectives

The objectives of this study were: (i) to evaluate the distribution of nitrate nitrogen in the soil profile in farms with irrigated vegetables, and (ii) to evaluate the risk of nitrate losses by leaching from the root zone during period without plant cover, from late autumn to early spring.

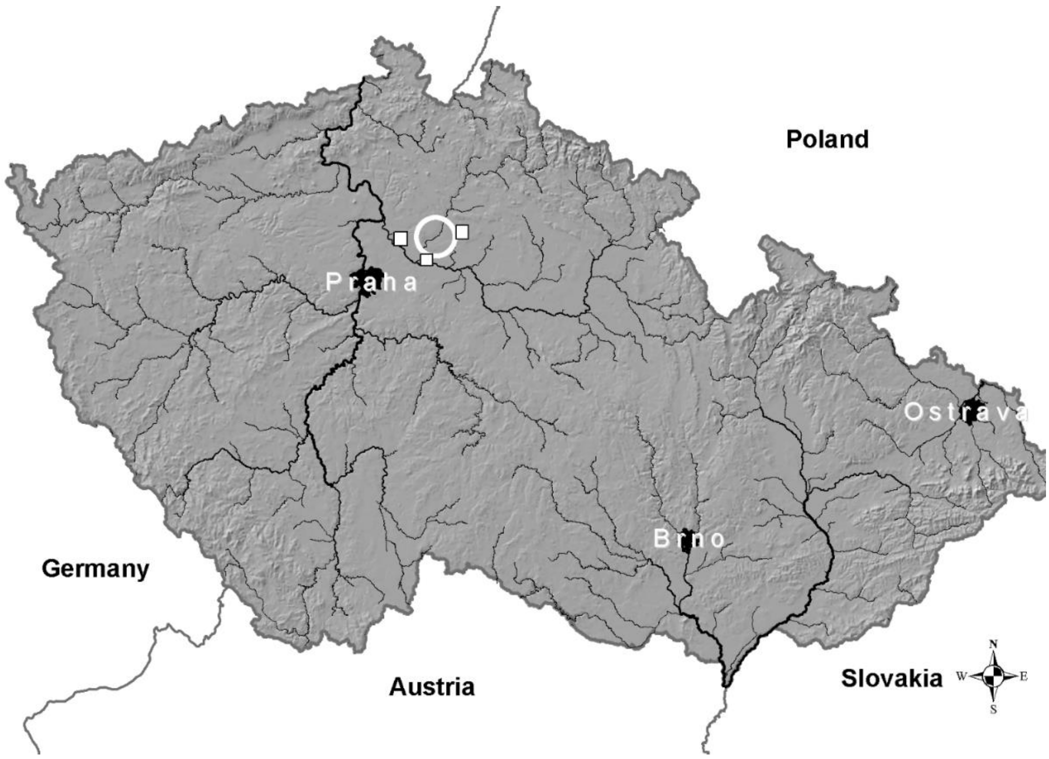

Fig. 1. The area of interest at lower Jizera river (circle) and the position of climatological stations (squares)

MATERIALS AND METHODS

The soil was sampled in the fields along the lower part of the Jizera river, between the villages of Sojovice (50.2139350 N, 14.7571592 E) and Kochánky (50.2757078 N, 14.7926503 E). Vegetables grown at monitored fields included: radish, lettuce, carrot, broccoli, onion, garlic, celery, parsley, cabbage, kohlrabi, red beet and early potatoes. Non-irrigated winter and spring wheat were irregularly included in the vegetable sequence.

N_{min} monitoring

Twenty three fields adjacent to the lines of collection wells were selected to represent areas with low or medium and increased concentrations of nitrates (over 50 mg $NO_3 \cdot dm^{-3}$) in the extracted water. Soil for soil moisture (gravimetrical) and mineral N, N_{min} (NH_4-N + NO_3-N) analyses were sampled with a hand-held corer (Eiejkelkamp, NL) in 30 cm segments to a depth of 120 cm on the onset of winter and at early spring. The samples were created by mixing soil from at least six different points. The soil was immediately put in a cool box and processed the same or next day according to the standard methods. Homogenized, 2 mm sieved soil was extracted with a 1% solution of K_2SO_4 (1 part of soil : 5 parts of solution) and analyzed on a Skalar spectrometer (Breda, NL). The nitrogen content was calculated from the N_{min} data and the moisture for each soil layer using the soil volume weight. Wherever relevant, the content was reduced according to its stone content.

Risk of leaching

The field water capacity (FWC) of the soil layers, needed for the simulation, was calculated with simple pedotransfer functions (PTF) from texture of soil (Haberle & Svoboda 2015). The FWC of top 60 cm soil ranged between 22 and 31% vol., soil under 60 cm had FWC between 21 and 32% vol. The amount of water (effective precipitation) needed to refill the water content to reach FWC level in the top soil and sub soil layers in autumn was calculated. The effective precipitation total from sampling term until the end of March was calculated from the water balance as the precipitation minus the potential evapotranspiration (Allen et al. 1998).

The risk of nitrate leaching was estimated as the proportion of initial nitrate content on the onset of winter leached below 30, 60, 90 and 120 cm, and calculated with the simple model, leaching equation of Burns (1976). The three experimental seasons belonged to the driest and warmest in 21st century. To simulate leaching under more representative weather conditions precipitation of winter 2012/2013 (165 mm from December to March, 12 mm more than average of previous winters of the 21st century), preceding experimental period, was used in combination with N_{min}, a soil moisture data of the three experimental years.

Root depth of the selected vegetables and potatoes grown in the fields was determined (not shown) and the data on root depth of both vegetables and field crops were tentatively categorized according to the literature and our published and unpublished data (Kristensen & Thorup-Kristensen 2007; Thorup-Kristensen & Sørensen 1999; Haberle & Svoboda 2014, 2015). The zones of nitrate leaching below 30 cm, 60 cm, 90 cm and 120 cm represent approximate effective depths of root depletion of groups of crops with shallow (early lettuce, radish), medium (potatoes, onion, garlic, spinach, carrot, celery, leek, root parsley, bean, pea, kohlrabi), deep (cereals, rapeseed, maize, cabbage, cauliflower, broccoli, red beet, turnip) and very deep root system (sunflower, sugar beet, clover and alfalfa, wheat and maize on fertile deep soils).

RESULTS AND DISCUSSION

Mineral N (N_{min}) content and distribution

The wide range of observed N_{min} contents during the experimental years and the layers are shown in the histograms (Fig. 2). Nitrate represented 85 to 92% of the N_{min} content in the experimental years; the weighted averages of the sites were about 95%. The similar high nitrate proportion was found in field crops (Haberle et al. 2009). The nitrate proportion was slightly lower in top soil. In individual fields, the nitrate proportion ranged to a greater extent, but a higher content of the ammonium form was found only in fields with a low content of N_{min}, mostly under 20 kg $N \cdot ha^{-1}$ ($R^2 = 0.42$).

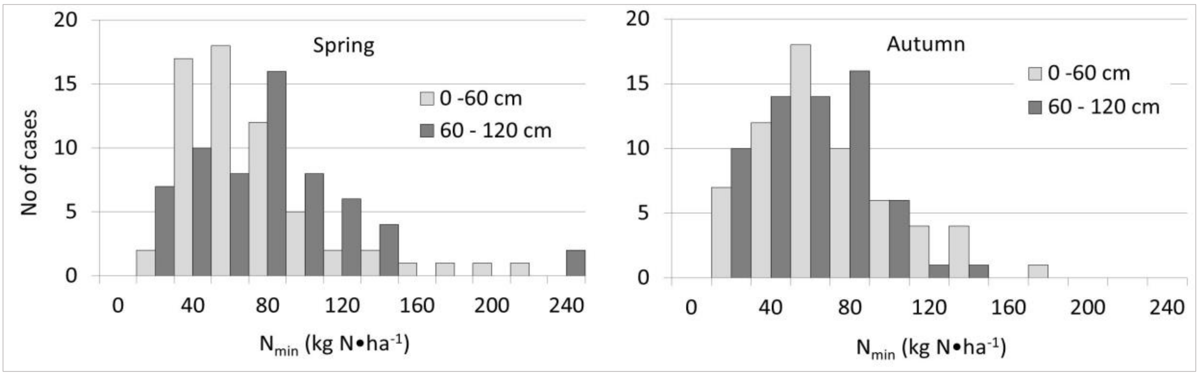

Fig. 2. Histograms of mineral nitrogen content in experimental years for 0–60 cm and 60–120 cm zones

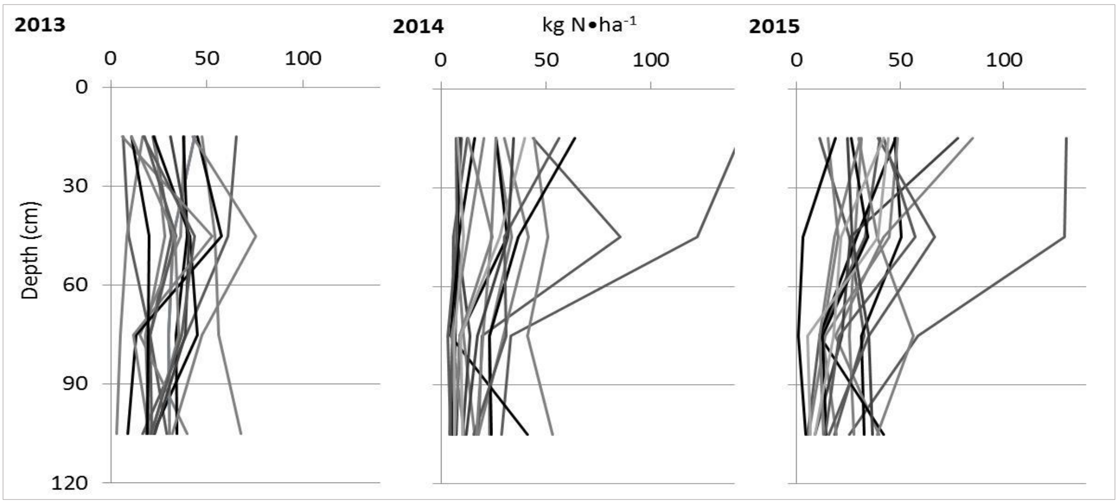

Fig. 3. Distribution of mineral N in the topsoil and subsoil layers. The lines show N_{min} distribution with depth in the monitored fields

The average N_{min} contents in the individual 30 cm layers were mostly under 40 kg N·ha^{-1} (75% of cases), and in 5% of cases (mostly in the top soil), it was over 70 kg N·ha^{-1}. The total content of N_{min} down to a depth of 120 cm was under 100 kg N·ha^{-1} in 45% of the cases, 20% of the cases were over 150 kg N·ha^{-1}. The average autumn mineral nitrogen contents in the fields, during the experimental years, ranged from 101 to 134 kg N·ha^{-1} in the 0–120 cm soil layer. The distribution of N_{min} ranged greatly among fields but, generally, similar contents in top- and subsoil layers were observed (Fig. 3). The average N_{min} content in the 60–120 cm zone, not available for most vegetables and potatoes, over the years ranged from 37 to 60 kg N·ha^{-1}. The high proportion of mineral N, mostly nitrate, in the deep subsoil, suggests there is a risk of N losses by leaching. For potatoes and many vegetables, the depth of 50–60 cm represents the limit under which the roots do not penetrate or the root density is too low for effective nutrient depletion.

The high (residual) N_{min} contents after harvest and before winter were observed after all the crops, as expected, after potatoes, lettuce, potatoes, broccoli, cabbage, celery, and surprisingly, also after onion and garlic – as well as during an extremely dry year 2015 after rain-fed wheats. Average N_{min} content before winter ranged from 107 kg to 147 kg·ha^{-1}, but the individual values ranged greatly (coefficient of variation 46–152%). Only in cruciferous vegetables, high N_{min} content after broccoli and cabbage (only two fields) was on average 239 kg N·ha^{-1}. Generally, the amount of N_{min} after harvest did not correspond to the common rating of vegetables with either a low or high risk as to a high residual nitrate content (Wu et al. 2005; Delgado et al. 2007). Further, the contents of N_{min} after the same species varied within a wide range, as the result of spring N_{min} content and distribution (from the previous year), fertilization rates and N uptake. This means that any evaluation of the risk of leaching can hardly be deduced only from the specific species of vegetables.

Evaluation of risk of nitrate leaching

The amount of water needed to refill the soil moisture to field capacity in the entire 0–120 cm zone was low in 2013 (on average 13 mm), due to the large late summer and autumn rains that year; they were medium in 2014 (44 mm); and high in the autumn of the exceptionally dry year 2015 (93 mm). The corresponding amount of water needed to refill at 0–60 cm was significantly lower: 7, 13, and 32 mm in 2013, 2014, and 2015, respectively. However, the wide range of the amount of water needed generated different risks of nitrate leaching in the individual experimental fields.

The precipitation at climatological stations in the region during the winters and correspondingly, the water balance surplus, were low, 34, 50 and 55 mm, during the three seasons. The conditions indicate a low risk of nitrate leaching into the deep layers. Calculations using the leaching equations of Burns (1976) showed that the specific conditions of experimental years generally prevented significant leaching of nitrate below the depth of 90 cm (Table 1).

Table 1. Average, minimum and maximum calculated amount and proportions of initial autumn $N\text{-}NO_3$ content leached below 30, 60, 90 and 120 cm. Besides effective precipitation in the experimental seasons (2013/2014 – 2015/2016), the leaching was also calculated with effective precipitation in the season 2012/2013

	Leached bellow 30 cm (kg N·ha^{-1})						Leached bellow 60 cm (kg N·ha^{-1})					
Autumn N_{min} data	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Effective precipitation	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016
Average	21	21	28	8	13	15	34	31	35	7	11	7
Minimum	1	4	7	0	2	3	4	6	5	0	0	0
Maximum	43	98	92	20	67	59	74	151	132	28	80	52
	Leached bellow 90 cm (in kg N·ha^{-1})						Leached bellow 120 cm (in kg N·ha^{-1})					
Autumn N_{min} data	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Effective precipitation	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016
Average	45	32	21	3	4	2	33	16	5	1	1	0
Minimum	5	5	0	0	0	0	4	1	0	0	0	0
Maximum	72	127	52	9	16	12	61	49	24	7	5	3
	Leached bellow 30 cm (in %)						Leached bellow 60 cm (in %)					
Autumn N_{min} data	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Effective precipitation	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016
Average	72	72	70	27	41	37	53	49	41	11	14	7
Minimum	66	67	65	0	25	26	37	37	23	0	0	0
Maximum	77	75	75	45	50	52	70	59	60	39	30	30
	Leached bellow 90 cm (in %)						Leached bellow 120 cm (in %)					
Autumn N_{min} data	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Effective precipitation	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016	2012/2013	2012/2013	2012/2013	2013/2014	2014/2015	2015/2016
Average	35	29	15	2	3	1	24	15	5	1	1	0
Minimum	23	15	0	0	0	0	15	2	0	0	0	0
Maximum	46	40	35	10	9	9	32	32	20	4	5	3

The average estimated nitrate leaching in years was low from both the topsoil (0–30 cm) and shallow subsoil (0–60 cm), with 27, 41 and 37% and 11, 14 and 7% of the initial content, respectively, in the experimental years. The average calculated leaching was negligible, 2%, under 90 cm. Average simulated amount of leached N reached maximum of 15 kg $N \cdot ha^{-1}$ from 0–30 cm zone in 2015. The comparison of leaching data from literature is not feasible considering the vast range of production, soil and weather conditions (Geypens et al. 2005); however, the authors agree that vegetables and potatoes pose increased risk of nitrate leaching (e.g., Neeteson & Carton 2001, Francis et al. 2003). The nitrate shifting from top to shallow subsoil may be extracted by subsequent crops. However, the comparison of N_{min} changes at the fields in the course of experimental years shows that it is often not depleted or even increases due to high N fertilization.

The three seasons were among the driest and warmest in the Czech Republic during the 21st century; in previous years, the precipitation in autumn and winter generated conditions for the shift of a significant portion of nitrate below 60 cm. When effective precipitation from winter 2012/2013, preceding experimental years, was used for N_{min} and soil moisture data of three years, the calculated leaching under 30, 60, 90 and 120 cm was on average 23, 34, 32 and 18 kg $N \cdot ha^{-1}$ (Table 1). The amounts corresponded to 71, 48, 26 and 15% of the initial content in the respective layers. It should be mentioned that the simple leaching model indicates the risk.

Nitrogen depletion

Although the monitoring was not aimed at the study of N depletion, our data confirmed the depth of apparent N depletion generally corresponds to root depth, in agreement with literature data (Kristensen & Thorup-Kristensen 2007; Kautz et al. 2013). Especially in non-irrigated wheats, with a high biomass and corresponding demand for N, long growth duration and deep root system, the soil N_{min} supply was effectively depleted. However, in the extremely dry year 2015, the stressed wheat left a great amount of residual N after the harvest. Our results suggest that specific crop rotations, alternating vegetables with low N efficiency and shallow roots and other crops (cereals, maize, sorghum) are effective tools for the reduction of the risk of leaching losses. These standard approaches of reduction of leaching and run-off losses (Cameira & Mota 2017; Li et al. 2017; Sainju et al. 2017) should be enhanced by new methods, such as the use of biofertilizers.

CONCLUSIONS

1. The study confirmed the high nitrate content in the topsoil and subsoil in vegetable farm fields with irrigation.
2. The data indicate a strong year and site variability in the risk of nitrate leaching. Nitrate shifted below 60 cm is often lost due to the shallow root systems of many vegetables together with the lower water capacity and stone content of the subsoil layers in some fields.
3. The reduction of leaching risk demand improved N management and the monitoring of available mineral N, not only in the topsoil but also in the subsoil zones with respect to specific N demand and root depth of vegetables and other crops.

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