The Changes of Soil Mineral Nitrogen Observed on Farms between Autumn and Spring and Modelled with a Simple Leaching Equation

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Abstract: The content of nitrate or mineral nitrogen (N_{min} = N-NO_3^- + N-NH_4^+) in soil in autumn is recognized as the indicator of potential risk of N leaching during winter. In this contribution, the apparent changes of N_{min} in the 0–60 cm soil layer, during winter, on farm fields in the Czech Republic were calculated. A significant positive relationship between N_{min} in autumn and the change during winter was observed in eight out of the nine farms. Nitrate N data produced similar relationships as N_{min}. The regression analysis suggested that 40–90% of N_{min} above a specific amount, 14–35 kg N/ha (interception of regression line, I_1), on farms was apparently lost from the soil zone. Corresponding results for pooled data (n = 187) were 74% and 25 kg N/ha (r = 0.90, P < 0.001). The proportion of N leached from the 0–60 cm layer, calculated with a simple leaching equation was significantly correlated (n = 187, r = 0.92, P < 0.001) with observed N_{min} change during winter, with the intercept (I_2) significantly different from zero (–30.9 kg/ha). When the average value of regression intercept I_1 of farms, or of pooled data, were introduced to the leaching equation as a constant correction parameter, the fit was satisfactory (r = 0.93 and 0.92, resp.) and the intercepts (–3.1 kg and –5.4 kg N/ha, resp.) were not significantly different from zero (at P < 0.01). The results of the study support the use of autumn N_{min} within the leaching equation as a robust indicator of the risk of N leaching.

Keywords: N_{min}; nitrate; risk; leaching equation; soil; precipitation; farms

Agriculture activities, especially intensive plant production on arable soil characterized by high doses of nitrogen and organic farm fertilizers, are one of major contributors to nitrate pollution of ground and surface waters (*e.g.* Boumans *et al.* 2005; De Ruijter *et al.* 2007; Kvítek *et al.* 2009). For example, Fučík *et al.* (2008) demonstrated a strong relationship between the proportion of arable land ratio within a catchment and water nitrate concentration. In 1991, the Nitrates Directive (91/676/EEC), concerning the protection of waters against pollution caused by nitrates from agricultural sources, was adopted. In 2003, the Nitrates Directive was implemented into Czech legislation, and nearly half of all agricultural land was designated as vulnerable zones (Figure 1). Stipulated compulsory restrictions on fertilizer, manure and slurry use, and crop rotations are aimed at the reduction of leaching risk; however, the Czech Code of Good Agricultural Practices and Action Programme do not specify any limit of nitrate content in soils.

Besides the monitoring of water quality (*e.g.* Kolář *et al.* 2002; Ruiz *et al.* 2002; Boumans *et al.* 2005; Fučík *et al.* 2008; Kvítek *et al.* 2009), indicators of the risk of nitrate leaching (at scales from farm to the whole country) are needed in order to ascertain whether the policies and regulations related to the protection of ground and surface waters are effective (Simmelsgaard 1998; De

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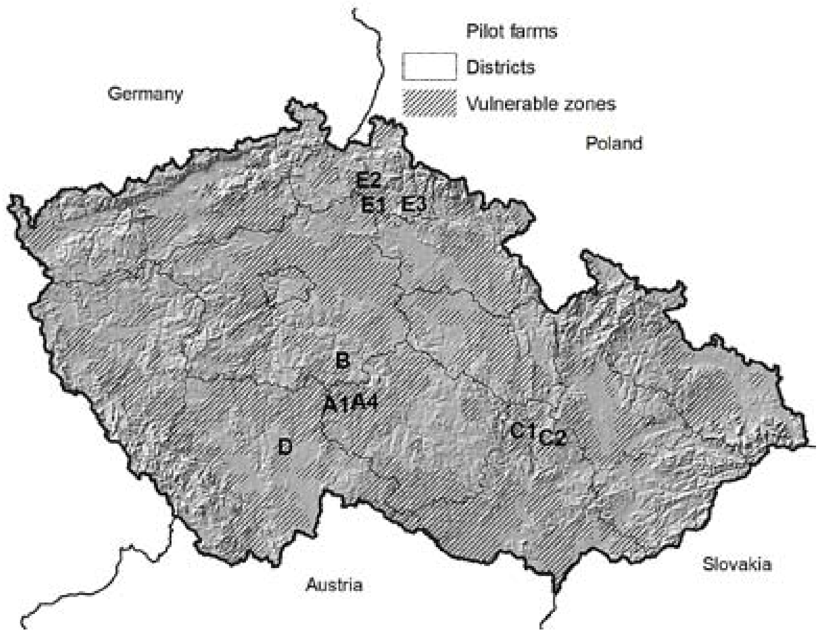

Figure 1. The location of monitored farms (A1 is located between A2 and A3)

Jong *et al.* 2007; De Ruijter *et al.* 2007). Residual N_{min} (N_{min} = N-NO_3^- + N-NH_4^+), or nitrate N after harvest or before the onset of winter, whether observed or calculated, have been used as a simple indicator of the risk of nitrate leaching during the inter-crop season (*e.g.* De Jong *et al.* 2007). Its utility is sometimes disputed with respect to the complex dynamics of soil nitrogen (Van Der Ploeg *et al.* 1995). Sophisticated models, with different degrees of complexity (*e.g.* LEACHN, RZWQM, SOIL-N, CANDY, SUNDIAL), are used to simulate N dynamics and losses; however, the use of these models for practical purposes is limited by the deficiency of detailed input data. The demand for a simple robust method, enabling a rapid indication of risk of N losses from the farm to the national scale, is satisfied with indexes of nitrate vulnerability, N calculators, and simple models utilizing N_{min} data and leaching equations (Ruiz *et al.* 2002; Delgado *et al.* 2006; De Jong *et al.* 2007).

Burns' leaching equation

A simple model of non-reactive solute transport through the soil, specifically for nitrate leaching, was developed and verified by Burns (1975, 1976). Burns' leaching equation is based on the field capacity of soil (FC) and the amount of infiltrating, percolating water. According to the classification of Addiscott and Wagenet (1985) it is a deterministic, functional model, based on capacity parameters. The authors appreciate it as a useful model for management purposes. The equation is one of the few that has been applied to practical problems (*e.g.* Burns 1980; De Neve & Hofman 1998; Ruiz *et al.* 2002). Moreels *et al.* (2003) showed that with a simple N mineralization module the Burns' model predicted the nitrate content better than did more complex models. The authors concluded that under conditions of limited data availability, a simple management model, needing only a limited number of parameters, may yield better simulation results than complex mechanistic models. The simplicity and utility of Burns' leaching equation has gained attention; several authors have analyzed the validity of the equation and some of the authors' assumptions (Magesan *et al.* 1999). Scotter *et al.* (1993) analysed the equation, using transfer functions, and concluded that it is consistent with an "independent flow tube" soil leaching model; rather than the soil solution being well-mixed at each soil depth, as suggested by Burns (1975). According to the analysis, the flux and the resident soil solution concentration profiles are shown to be quite different, but this does not prevent its use for quantitative calculations.

The objective of our study was to compare the apparent mineral nitrogen changes during the winter on farm fields with the outputs of this simple leaching equation.

MATERIALS AND METHODS

The fields of nine farms in the Czech Republic (Figure 1) were sampled for their content of mineral nitrogen (N_{min}= N-$N0_3^-$ + N-NH_4^+) in late autumn and at the end of winter (or early spring) in the years 2000–2005. The monitoring programme was performed within the activities connected with the adoption of the Nitrate Directive (91/676/EC) in the Czech Republic. The sampling focused on farms in a region where both soil-climate and agriculture production conditions suggested a higher risk of nitrate leaching (farms A and B, Figure 1); this is where over 38% of the data were acquired. In total, 187 pairs of autumn/spring N_{min} data were collected. The fields were mostly Luvisols and Cambisols, but no detailed pedological data were available. In some cases the soil type had to be derived from soil maps. Over 90% of sampled fields in groups A–C falls under medium soil, the others are medium-light (loamy-sand). Fields at farm D are medium (20%) to heavy gleyic soils (80%). The farms C and D are situated in a drier region than the other farms; and group E represents medium and medium-heavy soils. The altitude, average precipitation between sampling terms and basic climatic characteristics (derived from digital climatic maps of the country) are given in Table 1. The sampled fields comprised various combinations of preceeding crops, fallow soil, or winter crops; in some fields, manure or slurry was applied after the harvest of the main crop. Usually, but not always, the same fields were sampled in experimental years. The farms were monitored for 2–4 seasons within the experimental period. The number of samples from the farms varied; from A through E it was 76, 30, 41, 30, 10.

At each field, soil cores were taken with a gouge auger at 10–16 locations with a *ca* 25 × 25 grid from the topsoil (0–30 cm) and the subsoil (30 to 60 cm). GPS was used to sample the same area in autumn and spring. Soils were sampled before winter (2nd–23th November) and at the onset of spring (4th–30th March). The processing of samples followed standard procedure; samples were kept in a cooler during sampling and kept in a refrigerator to be processed the next day. Soil was shaken in 1% K_2SO_4, 1:5 soil:solution ratio for 1 h, NO_3^- and NH_4^+ were determined by colorimetry (SKALAR, FIA). The amount of N (in kg/ha) was calculated with the same value of soil specific weight. The apparent changes of N_{min} and nitrate N content between autumn and spring were calculated, and the relationship between the autumn content and the changes were examined with regression analysis using UNISTAT and MS Excel programmes.

Leaching equation

The amount of nitrogen leached below the depth 60 cm was calculated with a simple leaching equation (Burns 1975, 1976), in a form independent

Table 1. The summary of average climatic conditions (1971–2000) and average precipitation between sampling terms in experimental years at farms

	Farms						
	A1	A2	A3	B	C	D	E
Altitude (m a.s.l.)	500–600	500–550	500–600	350–450	350–550	425–450	300–500
Average precipitation between sampling terms (mm)	169	191	191	198	145	124	175
Average year precipitation (mm)	627	559	627	627	627	559	627–715
Average precipitation November–April (mm)	246–273	227–246	236–241	228–240	216–254	211–214	270–356
Average year temperature (°C)	6.5–7.0	6.5–7.5	6.5–7.0	7.5–8.0	6.5–8.0	7.0–7.5	6.5–8.0
Average day of year with temperatures > 0°C	59–64	59–62	58–63	53–61	58–62	60–62	52–62

of the layer's thickness (Towner 1983; Scotter *et al.* 1993)

$$X = \exp(-z\,\theta/I) \qquad (1)$$

where X is the fraction of nitrate solute at the soil surface leached below the depth z (cm) in a soil, with a volumetric soil water content at field capacity (FC) θ (cm/cm^3), by cumulative drainage I (mm) equal to the effective precipitation (rainfall less evaporation).

In the case of a homogenous distribution of solute in the soil profile $z = z/2$, for homogenous distribution of solute to depth $z0$ is $z = z - z0/2$ (Burns 1976; Scotter *et al.* 1993). We calculated leaching for the 0–60 cm layer, assuming a homogenous distribution (z = 30 cm), because accounting for a different proportion of N_{min} in the 0–30 cm and 30–60 cm zones did not improve the fit with the observed data. The calculation was performed using the autumn amounts of nitrate N and N_{min}. As shown by Addiscott and Cox (1976), when the effects of successive percolations (instead of a cumulative one) are considered, the differences in the calculated leaching were not significant. The leaching was calculated with a field capacity (FC) of 15% (except 25% for farm D) and additionally the FC of 20%, and 25% (30% and 35% for farm D) was used to ascertain the sensitivity of the model (see Discussion). The effective precipitation between sampling terms was calculated as the observed sum of rainfall reduced by 15%. The calculation of winter evaporation is difficult task even with detailed input data and it is beyond the scope of the study. Average month data of open water evaporation given in the Climate atlas of Czechia (Tolasz *et al.* 2007) for period December–January and November and February are about 10 and 14 mm, resp., but the actual evaporation from soil is lower due to limitation of water flux to surface and other factors (e.g. Shuttleworth 1991).

RESULTS AND DISCUSSION

N_{min} content in farms

The content of mineral nitrogen (N_{min}) in topsoil and subsoil was determined at several farms in November and in March during the years 2000 to 2005. The amount of N_{min} in the 0–60 cm zone in autumn moved over a wide range, 34% of the data were between 50 kg and 100 kg N per ha, and 10% were above 150 kg N/ha (Figure 2). There are no stipulated "tolerable, safe" limits of mineral N in the soil in the Czech Republic. According to the SchALVO directive of the state of Baden-Wuertemberg, farmers were not allowed to have more than 45 kg/ha mineral N (assuming it is mostly NO_3-N) in the 0–90 cm zone in order to be eligible for a compensation payment. As demonstrated by Van Der Ploeg *et al.* (1995), the amount of N_{min} may be too high

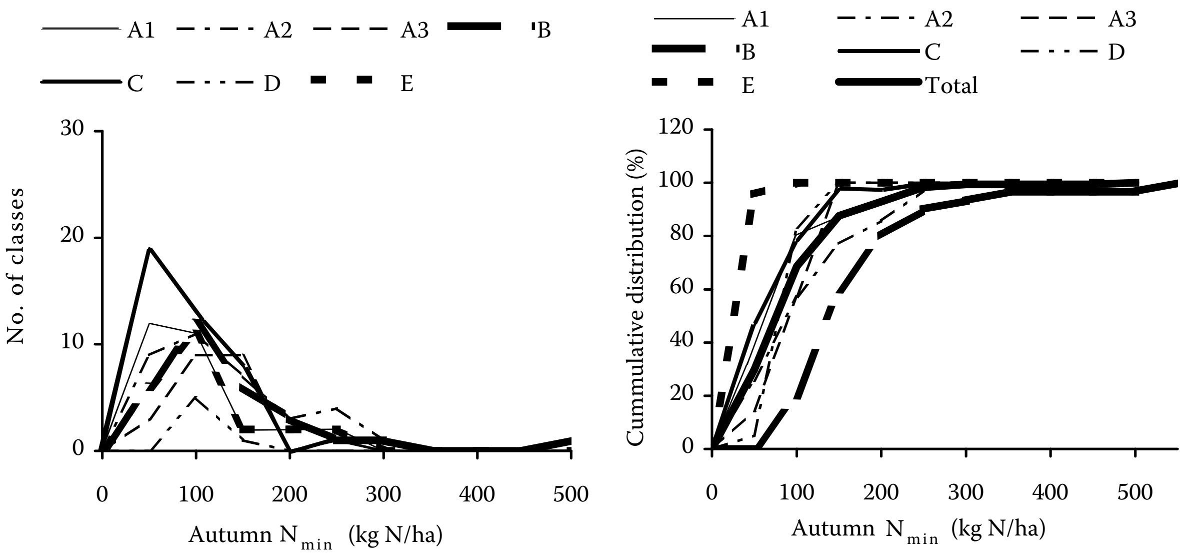

Figure 2. The frequency (left) and cummulative (right) distributions of autumn N_{min} data; total number of analyzed samples was 187

for some conditions; whereas for others it may be too restrictive, with respect to specific limits of nitrate leaching or concentration in leachate. The lowest N_{min} contents were observed at farms E. The extreme value 495 kg N/ha in 0–60 cm was found in the field where, untypically, clover crop was ploughed-in with a farmyard manure (farm B). However, sporadically a high level of N_{min}, over 200 kg N/ha in top soil could be found in farm fields (Anonymous 2009), therefore we did not excluded it from analysis.

The relation between autumn N_{min} and the change of N_{min} during winter

The data from most of farms and years showed a significant ($P < 0.01$) positive relationship between mineral N (N_{min} or N-NO_3^-) content in autumn and the change (mostly a decrease) of N in the 0 to 60 cm zone during the winter. On the average of years and farms, the correlation coefficient was 0.87 and 0.86 for nitrate N and N_{min}, resp. Nitrate N usually constituted over 90% of N_{min} in the autumn. As the ammonium is transformed into the nitrate form relatively easily, we used total mineral N (N_{min}) here, as the relevant robust indicator of the risk of N leaching (Van Der Ploeg *et al.* 1995; Köhler *et al.* 2006; De Jong *et al.* 2007). In the regression data set, several outliers could be found (Figure 3). Some of them were evidently the result of enhanced nitrogen mineralization, due to the application of slurry or manure; especially when applied shortly before the sampling term. Nevertheless, a few data, for which no obvious biological explanation or sufficient data on management were available, decreased the fit.

When all of the data was pooled ($n = 187$, $r = 0.90$, $P < 0.001$), the slope of the linear regression of the autumn N_{min} content on N_{min} change during winter suggested that 74% of autumn N_{min} was apparently lost from the 0–60 cm zone. On the farms, the slope of the regression line (pooled data of experimental years) suggested the apparent losses of from 54 to 90%. The intercepts of the regression showed that the losses occurred above the specific autumn content, 14–36 kg of N_{min} per ha; when all data were pooled the intercept was 25.6 kg/ha (Figure 3). The similar aggregation of data at different levels was used by De Ruijter *et al.* (2007), for example. The positive intercept is probably the result of mineralization of N from soil organic matter that partially compensated for the leaching losses. Enhanced mineralization was indicated by a higher proportion of ammonium N in the 0–30 cm layer at the spring sampling term, especially on fields with a high input of manure or slurry the previous autumn.

Other biological processes, such as immobilization, denitrification, and the volatilization of N determine the apparent N_{min} changes during the winter. The simulation with the CANDY model (Franko *et al.* 1995) using input data representative for monitored field confirmed that the loss of nitrate, due to leaching, was partially replenished by the mineralization of N (not presented). According to the simulation, leaching was the dominant factor; gaseous losses being one to two orders of magnitude lower than leaching. The interactive effect of mineralization during the inter-crop period

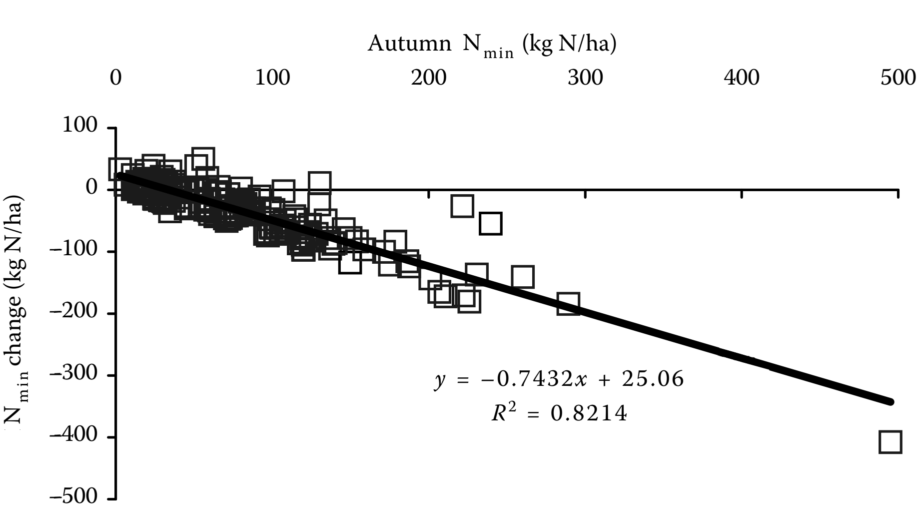

Figure 3. The relationships between autumn N_{min} content in 0–60 cm zone, and the change of N_{min} content during winter for pooled data from farms and years (N = 187).

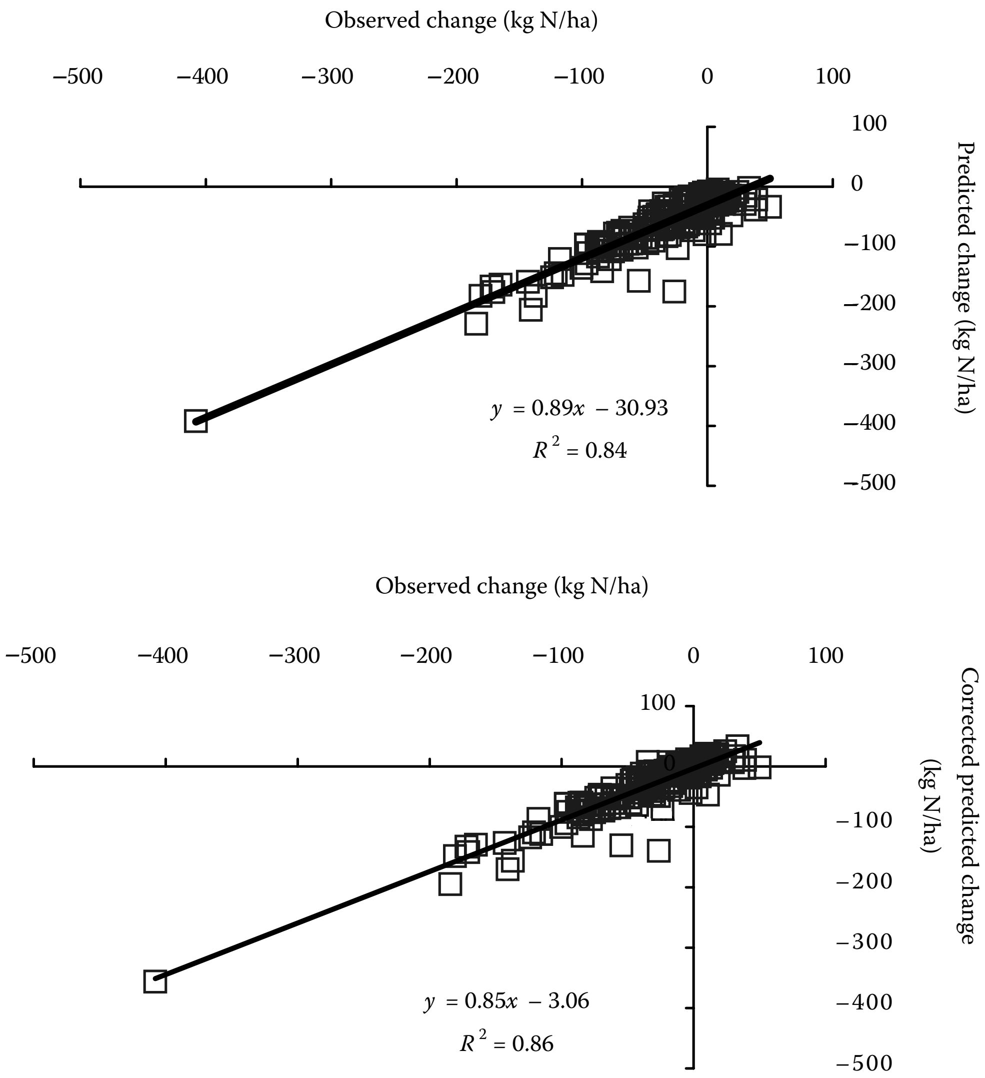

Figure 4. The relationships between the observed and predicted N_{min} change during winter (above) and between observed and predicted N_{min} change with correction (bottom)

has been demonstrated in numerous simulation studies and experiments (*e.g.* Klír *et al.* 1987; Simmelsgaard 1998).

Calculation of leaching

The amount of N leached from the 0–60 cm layer, calculated with a simple leaching equation (Burns 1975, 1976), was on most farms and years significantly ($P < 0.01$) related to the observed data of the apparent N changes during the winter. When nitrate N data were used, the relationship improved slightly in a few cases but worsened in others. When all data was pooled (Figure 4) the relationship was good ($r = 0.91$, $P < 0.001$), even when the extreme value of 495 kg/ha in the autumn was not included ($r = 0.88$). The intercept of the regression (I_2) was significantly different from zero, as expected from the positive regression intercept of the observed autumn content, on the apparent changes during the winter (I_1) (Figure 3).

Seeing that the aim of this study was to verify the use of autumn mineral N in the leaching equation as a robust indicator of N leaching, we introduced the regression intercept from of the observed data on farms (I_1) as a correction parameter in the leaching equation. The corrections were 26.7 to 35.7 kg N/ha in farms A to C, and 21.6 kg and 14.1 kg N/ha in farms D and E, resp. It is assumed the intercepts (I_1) indicate the mean level of composite N dynamics from the autumn to early spring, for the given set of natural and agricultural conditions. The same approach and generalization are the basis of the use of N calculators and indicators, especially at the regional scale (Delgado *et al.* 2006; De Jong *et al.* 2007; De Ruijter *et al.* 2007, and others).

The introduction of the empirical correction parameter improved the relationship between the modelled and observed changes during winter, such that the intercept of pooled data (I_2) 3.06 kg N/ha was not significantly different from zero (Figure 4). The slope of the regression was 0.85, suggesting that the model still underestimated the apparent loss during winter. Using a weighted average of correction parameters (intercepts I_1) of the farms (28.9 g N/ha) or the intercept of all pooled data (25.5 kg N/ha), changed the results little ($y = 0.8856x - 1.1905$, $r = 0.92$ and $y = 0.8875x - 0.973$, $r = 0.92$, resp). Our results suggest that the leaching equation is a reasonable indicator of leaching, but it is not suitable for quantification of the N load of leached nitrate, without one also accounting for the N mineralization (and other processes) during the leaching period (Van Der Ploeg *et al.* 1995; Moreels *et al.* 2003).

The factors affecting calculated leaching

The utilization of leaching equations is based upon several assumptions and simplifications, such as homogenous soil layers and the disregard of N transformations. Further, physical soil characteristics and actual moisture before winter vary, due to local weather conditions, the preceding crop, soil management, etc. (Vaněk *et al.* 2003); yet another factor being the variability of spatial N_{min} within a sampled field (Illsemann *et al.* 2001; Haberle *et al.* 2004).

The use of rather low FC values is supported, for example by White *et al.* (1986) who found fractional transport volumes much smaller than the field capacity. Scotter *et al.* (1993) suggested that the water content parameter in the leaching equation is not necessarily the water content at FC; as when preferential flow occurs, not all the soil water participates in solute transport. They proposed an alternative definition of field capacity as the water content involved in solute transport to be defined operationally from experiments. The map published by Doležal *et al.* (2006) indicate the monitored farms are situated mostly in regions with a high proprotion of soils where preferential flow is significant. Magesan *et al.* (1999) treated FC as an unknown parameter, evaluated by fitting results of the leaching equations to sets of data in their study. According to Addiscott and Cox (1976), the Burns' (and other simple) equations underestimated the leaching of nitrate unless the most inaccessible soil water was left out of the calculation, and the best results were obtained when only gravitational water was taken into account.

Effective precipitation is the second deciding parameter of the leaching equations. Again, several factors inevitably modify the amount of water entering and percolating. Accounting for soil evaporation (temperature), snow cover, or conditions for runoff in the form of simple indicators (correction coefficients) may improve the estimation of effective precipitation. We reduced rainfall by 15%; that being a rather rough estimation, but we had not enough data on the sampled fields. According to leaching equation, using the higher reduction of rainfall, e.g. 25%, decreases the calculated leaching by 3–4.5% at light to heavy soil, resp. The calculation of evaporation from soil during winter is complicated by periods of freeze and snow cover, data given in literature vary greatly among authors. According to Schmidt *et al.* (2008), from the six most important uncertainties of nitrate leaching at the regional scale, ± 48% represented the lack of exact knowledge about agricultural land use management; soil parameters +4% to –52%; while precipitation (intervals 500–600–700 mm) accounted for only 12%. The relatively low sensitivity of modelled N leaching within the range of the seepage rate (= effective precipitation here); 1.0–2.0 mm/day and at FC = 0.2 cm/cm^3 described Van Der Ploeg *et al.* (1995). In our experiment, the average daily rainfall from November to March in the regions of the farms were in the same interval of 1.0 to 2.0 mm/day in the seasons 2000/01–2004/05; except for the Liberec meteorological station (387 m a.s.l., farm E2), where up to 2.5 mm/day was observed. When using leaching equations it is often assumed that soil is at field capacity in the autumn (*e.g.* Van Der Ploeg *et al.* 1995), but that is surely not true in dry years (Renger 2002). We observed none to little increase of soil moisture between autumn and spring sampling terms (except for 2003); however, allowing for the replenishment of soil water may improve reliability of the leaching equation, especially in soils with a high FC and in dry years.

It should be stressed that nitrogen leached below 60 cm is still accessible to the roots of most crops (e.g. Sauer *et al.* 2002; Haberle *et al.* 2006). Leaching equation suggests that 35–70% of nitrate at 0–60 cm may be leached below 100 cm under soil and climate conditions of the experimental farms. Generally, the deep layers under one meter are difficult to deplete for most crops. Also, the nitrate in deeper subsoil layers, often with a greater proportion of coarse sand and parental material (e.g. De Ruijter *et al.* 2007) is prone to leaching from the root zone by spring rainfalls; especially under late sown crops, donated with high doses of mineral and organic fertilizers (potatoes, maize). Hence, the evaluation of leaching risk should also include the ability to follow the main crop's extraction of nitrogen from deeper subsoil layers (Delgado *et al.* 2006).

CONCLUSIONS

The results of this study support the use of N_{min} in autumn, for an indication of N losses with a simple leaching equation in medium and medium-light soils. The leaching equation may help to indicate the risk of N leaching, and to compare the risk under different combinations of soil and climate conditions. From the results on several farms, the use of a correction factor (here about 25–30 kg N/ha), accounting for mineralization of N may possibly be recommended. The correction factor is both site-specific and farm-specific, and should be estimated according to the results of the sampling of the representative fields, with typical management practices.

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