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Nitrate leaching in forest ecosystems is related to forest floor C/N ratios

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Abstract

Relationships between nitrogen (N) output with seepage water and forest floor C/N ratios were analysed by use of three independent datasets: (i) a compilation of input–output studies in temperate forest ecosystems in Europe; (ii) a seven-year national Danish survey of nitrate concentrations in forest soils; and (iii) a similar one year Dutch survey. Nitrate leaching and nitrate concentrations were negatively correlated with forest floor C/N ratios in all three datasets, though the correlation was weak in the Dutch dataset. Sites with a C/N ratio below 25 leached nitrate or had elevated nitrate concentration in the three datasets. Nitrate was not present in the subsoil at sites with C/N ratios above 30 in the European and Danish data. In the less intensively monitored Dutch forest soils nitrate concentrations at C/N ratios above 30 were variable. Forest floor C/N ratios may be used to assess risk for nitrate leaching in conifer stands using >30, 25 to 30, and <25 to separate low, moderate, and high nitrate leaching risk, respectively.

Keywords: Forest ecosystems; forest floor; nitrate leaching; nitrogen deposition; risk assessment

Introduction

The nitrogen (N) deposition to many European forests exceeds the capacity of the ecosystem to retain nitrogen by assimilation in trees and microbes. Compilations of input–output studies in temperate forest have shown that a major part of the investigated sites that receive more than 10 kg N ha^{-1} $year^{-1}$ in throughfall experience nitrate output above 5 kg N ha^{-1} $year^{-1}$ (Dise and Wright, 1995; Gundersen, 1995). However, there was not a direct relationship between N output and N inputs: At N inputs from 10 up to 60 kg N ha^{-1} $year^{-1}$, no retention and almost full retention could be found (Gundersen, 1995). Understanding this variability in forest ecosystem response to nitrogen input is essential to the assessment of pollution risks and to calculations of critical loads.

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Detailed process studies at forested sites within the European N deposition gradient in the NITREX (Nitrogen saturation experiments) network showed that nitrate leaching was more related to an index for ecosystem 'N status' than to the N input (Gundersen et al., 1998). The 'N status' index was based on a range of interrelated N characteristics and internal N fluxes such as mineralisation and N flux in litterfall. Responses to experimental manipulations of N input (N addition or N removal) at the same sites further supported these results (Gundersen et al., 1998). In order to apply such information on a broader scale it is necessary to identify indicators of N status, which can be easily obtained. Nitrogen concentration in foliage and foliage litterfall, forest floor N concentration or C/N ratio, and N flux in litterfall may be possible indicators of forest ecosystem N status (Gundersen et al., 1998; Tietema et al., 1997). Recent analyses of European databases indicate an empirical relationship between forest floor C/N ratio and nitrate leaching (Gundersen, 1998), and an especially strong relationship between C/N ratio and nitrate leaching was found for Norway spruce in Central Europe (Matzner and Grosholz, 1997).

This paper analyses the relationship between nitrate leaching and forest floor C/N ratios in three independent datasets with different temporal and geographical resolution. The aim is to test the robustness of such an empirical relationship, and to discuss whether forest floor C/N ratios can be used as indicator for N status of forest ecosystems.

Methods

Three independent data sets were used in the analysis: (1) a compilation of data from plot-scale input–output studies in European forests; (2) a seven-year national Danish survey of soil water nitrate concentrations in forests; and (3) a one-year national Dutch survey of soil water nitrate concentrations in forests.

Input–output fluxes of nitrogen (N) and other ecosystem data from 77 forest ecosystems (17 deciduous and 60 coniferous sites) over Europe have been compiled in a database (Element Cycling and Output-fluxes in Forest Ecosystems in Europe — ECOFEE) (Gundersen, 1995). The emphasis in ECOFEE is on plot-scale studies in mature stands, including plots within studied catchments, since possible relationships between N fluxes and ecosystem characteristics will be most pronounced on a plot scale. The sites included were investigated for a minimum of two years in the period 1985 to 1995. Average N fluxes in bulk precipitation, throughfall, litterfall, leachate below the root zone (output) and N concentrations in various compartments were included along with general site and stand characteristics. Here we only discuss nitrate leaching losses, since they normally account for more than 95% of the output. The quality of data on output fluxes may be variable between sites since different methods (hydrological modelling, Cl-budgets, or stream runoff) have been used to estimate the output water flux in the original investigations. Forest floor C/N ratios were if specified calculated from C and N pools in the O_l, O_f and O_h horizons (the whole organic layer without freshly fallen litter). Even though C/N ratio in the forest floor is much easier to measure than nitrate leaching, some uncertainty and differences in methods may be expected for this parameter as well.

In the Danish survey, sites were chosen systematically in a 7×7 km grid (Callesen et al., 1998). Totally 111 forest sites where included. Soil samples were taken at 75–100 cm depth twice a year during the dormant season in 1986–89 and monthly during the dormant season in 1990–93, in total 25 sampling occasions per site. At each occasion composite samples consisting of 16 augured subsamples were made. Following an extraction with 1 M KCl for 2 hours nitrate was determined. Actual water content in the soil samples was determined and used for expression of the soil solution concentration of nitrate. Only mean concentrations over the measurement period were used in this paper since no time trends were detected in the data (Callesen et al., 1998). At 31 of these sites (which are part of the ICP Forest Level I monitoring programme) forest floor C/N ratios have been measured by standardised methods (Vanmechelen et al., 1997).

In the Dutch survey, 150 sites were chosen to compare with a 0.5×0.5 km groundwater monitoring network and to cover seven common tree species (de Vries and Jansen, 1994). Soil samples for determination of nitrate concentration were sampled from 60 to 100 cm depth once at each site in the period 15 Feb. 1990–16 May 1990. A composite sample of 20 subsamples from within a 20×20 m square was obtained from each site and nitrate was determined in soil water extracted by centrifugation (de Vries and Jansen, 1994; de Vries et al., 1995).

Results and discussion

European dataset

In the ECOFEE dataset, N input (measured as inorganic N in throughfall) accounted for 48% of the variation in nitrate leaching and on average 60% of the N input was leached (Fig. 1). Sites with strong N retention ranged even throughfall up to 60 kg N ha^{-1} year^{-1}, whereas sites with no retention could be found over the whole range of elevated N inputs (10–60 kg N ha^{-1} year^{-1}). The N retention at high input may be related to the dominance of ammonium in the input at these sites, since ammonium is less mobile in the soil than nitrate (Dise et al., 1998a; Gundersen, 1995). In a thorough analysis of the ECOFEE dataset, Gundersen, 1998) found significant correlations between nitrate leaching and several parameters (N concentrations in foliage, foliage litter and forest floor material, and N flux in litterfall) especially when separating conifers and broadleaf forest sites. The most pronounced relationship including both forest types was between nitrate leaching and forest floor C/N ratio ($r^2 = 0.39, n = 31, p = 0.0002$) (Fig. 2). Log-transforming values for nitrate leaching improves the model ($r^2 = 0.60$). There was no correlation between nitrate leaching and the C/N ratio of organic matter in the mineral soil (0–30 cm) (Gundersen, 1998). Adding throughfall input to the log-linear regression model improved the model fit:

$$\log_{10}(NO_3\text{-leaching}) = 0.014(\text{N-throughfall}) - 0.11(\text{C/N-forest floor}) + 3.4$$
$$r^2 = 0.69, n = 33, p < 0.0000$$

The uncertainty in predicting nitrate leaching based on this empirical model will still be at least 10 kg N ha^{-1} year^{-1}. Other factors like soil type, tree species, climate, stand age influence leaching as well (Wilson and Emmett, 1998). We also need to consider the differences

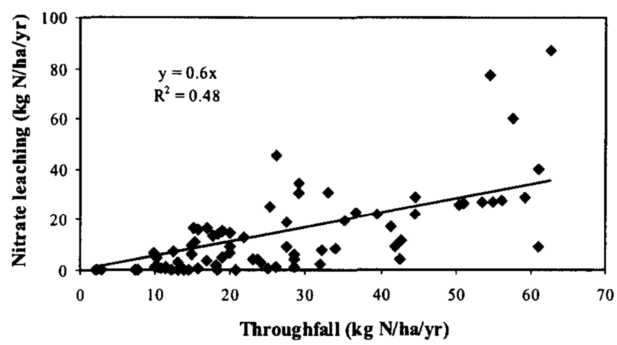

Fig. 1. Input–output relation for 77 temperate forest ecosystems in Europe (ECOFEE database). Leaching losses are estimated from continuous sampling (>2 years) of soil water below the root zone combined with some kind of simple hydrological modelling. Methods vary from site to site. Updated from Gundersen (1995).

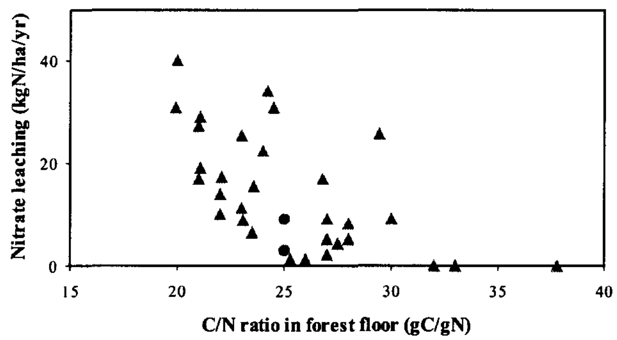

Fig. 2. Nitrate leaching vs C/N ratio at 33 temperate forest (▲ conifer, ● broadleaf) sites in Europe (ECOFEE database). See Fig. 1 legend.

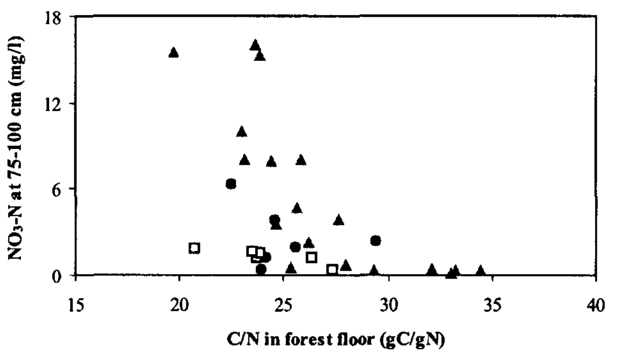

Fig. 3. Nitrate concentration in soil water at 75–100 cm depth vs forest floor C/N ratio at Danish ICP Forest Level I sites (▲ mature conifer; ● mature broadleaf; ❑ young stands, <20 years). Nitrate concentrations are means over seven years of sampling in the dormant season.

in methodology exist among the sites, which especially adds to the error in the nitrate leaching data. Furthermore, the sites have not been selected systematically with respect to geography, soil types, forest types etc. Thus, the empirical relation must be used with caution. Despite these reservations, the data clearly suggest that sites with C/N ratios above 30 barely leach any nitrate, whereas sites with C/N ratio below 25 all leach more than 5 kg N ha^{-1} $year^{-1}$. At C/N ratios between 25 and 30 both full retention and high leaching occur (Fig. 2). Only two broadleaf sites were available in the dataset and they fell within the variability of the conifer sites (Fig. 2).

Danish dataset

In the Danish survey it was found that soil nitrate concentrations were influenced by soil type, forest type (culture, closed stand, decoration greenery, afforestation) and size of the forest area around the site (Callesen et al., 1998). No estimates of N input were available for each of the 111 sites, but a negative relationship to the size of the forest area was probably due to higher N deposition (and edge effects) in small forest areas, that caused soil nitrate concentrations to increase. At the subset of sites where forest floor C/N ratio was available, a clear negative relationship (r^2 = 0.60, n = 25, p < 0.0000) with soil nitrate concentrations (log-transformed) was found (Fig. 3). Sites with young stands (<20 years old) were excluded from the regression, since the demand for nitrogen is much higher in young stands, which build up relatively more N rich tissue in the canopy than mature stands (Fig. 3). Six out of the 25 sites held broadleaf stands, but they did not differ significantly from the conifer sites in an analysis of variance. Although we do not know the exact nitrate leaching loss at these sites, the results support the findings from the European dataset separating non-leaching sites at C/N ratios above 30 and sites with considerable leaching at C/N ratio below 24–25 (Fig. 3).

Dutch dataset

The Dutch survey data, which only represent a 'snapshot' of the subsoil nitrate concentration over one dormant season, did not show any relation to the forest floor C/N when all the data was included in the analysis. However, when the analysis was restricted to sites on well-drained soil with coniferous stands more than 20 years old a negative correlation between nitrate concentration and C/N ratio (r^2 = 0.19, n = 70, p = 0.0002) was found (Fig. 4). The subset of data do support the conclusion that sites with forest floor C/N ratio below 24–25 leach considerable amounts of nitrate (Fig. 4). The variability in nitrate concentrations at C/N ratios above 30 was rather high and no threshold could be identified. Besides the uncertainty caused by the short-term measurements (spring 1990), the higher variability in the Dutch data compared to the European and Danish data, may be caused by the differences in sampling date. In the Danish survey, significant differences in nitrate

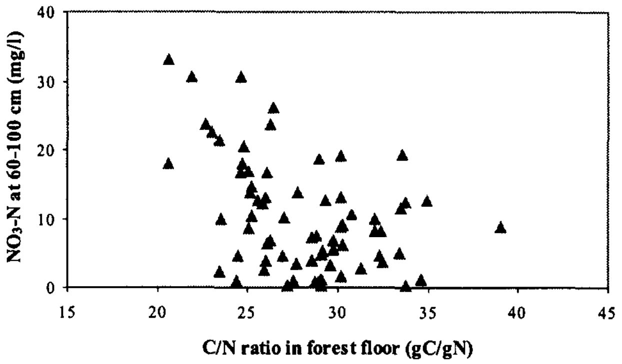

Fig. 4. Nitrate concentration in soil water at 60–100 cm depth vs forest floor C/N ratio at Dutch forest sites. Nitrate concentrations were measured once in Feb.–May 1990. The sites plotted are limited to well drained sandy soils with coniferous forests.

concentrations were found between months and years (Callesen et al., 1998). Further, samples from late dormant season may be somewhat dominated by hydrological transported nitrate directly from the deposition, than by microbial produced nitrate from the forest floor. However, replication of the sampling over the period (Feb.–May 1990) at 10 of the sites showed no clear trends in nitrate concentrations (de Vries and Leeters, 1998). Nitrate leaching was also estimated at the sites based on Cl-budgets and deposition estimates (de Vries and Jansen, 1994). The correlation between these nitrate leaching fluxes and the C/N ratio was low as well.

Discussion

Based on these three independent datasets we can separate three groups of sites according to the forest floor C/N ratio (Table 1). This simplified scheme may be used in assessment of nitrate leaching risk as a consequence of N deposition or disturbance of plant uptake. The datasets all support the lower threshold at C/N ratio 25 where nitrate leaching seem to increase. According to data in Vanmechelen et al. (1997) approximately 40% of the sites within the ICP Forest Level I monitoring network have forest floor C/N ratios below 25. A shift in ecosystem functioning around C/N ratio 25 is supported by investigations of the microbial processes in relation to forest floor C/N ratio (or N concentration). Nitrification rate is reported to increase significantly below C/N ratio 24–27 (or N% 1.4–1.6) (Kriebitzsch, 1978; McNulty et al., 1991; Wilson and Emmett, 1998). Once nitrate is formed in the forest floor it is apparently leached down the profile since nitrate immobilisation is low even at high C/N ratios (Gundersen et al., 1998; Tietema, 1998).

Table 1

Forest floor C/N ratio as a rough indicator of ecosystem N status in mature coniferous forest. Risk of nitrate leaching relate to cases where the forest receive more than 10 kg N ha^{-1} $year^{-1}$ in deposition

Forest floor C/N ratio (g/g)	Above 30	25–30	Below 25
N-status	N-limited	Intermediate	N-saturated
Risk for nitrate leaching	Low	Moderate	High

The threshold for the N-limited situation (C/N ratio above 30) is not as well supported due to a relatively small number of data in the European and the Danish datasets and the high variability in the Dutch dataset.

Due to the low number of broadleaf sites we can not be confident that the grouping in Table 1 is valid for broadleaf forests. Some further work to fill these gaps are necessary.

If forest floor C/N ratio is to be used as an indicator for N status or nitrate leaching risk the term forest floor needs to be specified. Ideally, the C/N ratio should relate to decomposed material accumulated above the mineral soil (O_f+O_h horizons). The O_l horizon is directly influenced by litterfall material and the C/N of this layer may thus vary seasonally. However, if the forest floor is substantial the inclusion of the O_l horizon in the measurement will not influence the overall C/N ratio of the forest floor. Stands with high decomposition rate and young stands on bare mineral soil have very thin forest floors which mainly consist of relative fresh decomposing foliage (no humus). In that case forest floor C/N may be measured as high (>40). For such systems the C/N ratio of the first 5 cm of the mineral soil may be the place to search for the controls on N leaching.

The sites included in the three datasets (Figs. 2, 3 and 4) all received N input >10 kg N ha^{-1} $year^{-1}$ and the ECOFEE data showed that N input also influence the output. The influence of N input was further analysed by Dise et al. (1998b) on a dataset including low deposition sites. At inputs <9 kg N ha^{-1} $year^{-1}$ there where no leaching irrespectively of the forest floor C/N ratio. They could make reasonable predictions of nitrate leaching from forest floor C/N ratio and N input in throughfall even when catchment scale data were included.

The C/N ratio of the forest floor may be changed by N deposition over time and this change seem to determine when the ecosystem becomes N-saturated. Long-term changes in forest floor C/N ratios have been documented from Central Europe (von Zezschwitz, 1985; Hildebrand, 1994). Data from N deposition gradients indicate that N deposition has changed forest floor C/N (McNulty et al., 1991; Gundersen et al., 1998; Falkengren-Grerup et al., 1998). In Europe low C/N ratios coincide with the high deposition regions (Vanmechelen et al., 1997). To be able to predict changes in nitrate leaching it is necessary to be able to predict the rate of changes in the forest floor C/N ratio. Further work to improve the predictive capability of the empirical relationships discussed will be important in this respect. A first step could be to fill the gaps in the ECOFEE database and increase the number of sites and to obtain C/N ratios for all the sites in the Danish survey. A second step could be to perform measurements in new or existing networks with comparable methods to reduce the error in the data.

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References

Callesen, I., Raulund-Rasmussen, K., Gundersen, P., Stryhn, H., 1998. Nitrate concentrations in soil water below Danish forests. Forest Ecology and Management. In press

De Vries, W., Jansen, P.C., 1994. Effects of acid deposition on 150 forest stands in the Netherlands. 3. Input output budgets for sulphur, nitrogen, base cations and aluminium. Wageningen, the Netherlands, DLO-Winand Staring Centre for Integrated Land, Soil and Water Research, Report 69.3, 60 pp.

De Vries, W., Leeters, E.E.J.M., 1998. Effects of acid deposition on 150 forest stands in the Netherlands. 1. Chemical composition of the humus layer, mineral soil and soil solution. Wageningen, the Netherlands, DLO Winand Staring Centre for Integrated Land, Soil and Water Research, Report 69.x.

De Vries, W., Van Grinsven, J.J.M., Van Breemen, N., Leeters, E.E.J.M., Jansen, P.C., 1995. Impacts of acid atmospheric deposition on concentrations and fluxes of solutes in Dutch forest soils. Geoderma 67, 17–43.

Dise, N.B., Wright, R.F., 1995. Nitrogen leaching from European forests in relation to nitrogen deposition. Forest Ecology and Management, 71, 153-161.

Dise, N.B., Matzner, E., Gundersen, P., 1998a. Synthesis of nitrogen pools and fluxes from European forest ecosystems. Water, Air and Soil Pollution. In press.

Dise, N.B., Matzner, E., Forsius, M., 1998b. Evaluation of organic horizon C:N ratio as an indicator of nitrate leaching in conifer forests across Europe. Environmental Pollution, 102 (S1), 453–456.

Falkengren-Grerup, U., Brunet, J., Diekmann, M., 1998. Nitrogen mineralisation in deciduous forest in south Sweden in gradients of soil acidity and deposition. Environmental Pollution, 102 (S1), 415–420.

Gundersen, P., 1995. Nitrogen deposition and leaching in European forests – preliminary results from a data compilation. Water, Air and Soil Pollution 85, 1179–1184.

Gundersen, P., 1998. Indicators of nitrogen status in European forest ecosystems. Hydrology and Earth System Sciences. In prep.

Gundersen, P., Emmett, B.A., Kjønaas, O.J., Koopmans, C., Tietema, A., 1998. Impact of nitrogen deposition on nitrogen cycling: a synthesis of NITREX-data. Forest Ecology Management 101, 37–55.

Hildebrand, E.E., 1994. Der Waldboden — ein konstanter Produktionsfaktor? Allg. Forst. Zeitschrift 49/2, 99–104.

Kriebitzsch, W.U., 1978. Stickstoffnachlieferung in sauren Waldböden Nordwestdeutschlands. Scripta Geobotanica, Goltze, Göttingen, Germany, 14, 1–66.

Matzner, E., Grosholz, C., 1997. Relationship between NO_3-output, C/N ratio of the humus layer and N-input in Central European spruce forest (*Picea abies* Karst.) ecosystems. Forstw. Cbl. 116, 39–44.

McNulty, S.G., Aber, J.D., Boone, R.D., 1991. Spatial changes in forest floor and foliar chemistry of spruce-fir forests across New England. Biogeochemistry 14, 13–29.

Tietema, A., Beier, C., de Visser, P.H.B., Emmett, B.A., Gundersen, P., Kjönaas, O.J., Koopmans, C.J., 1997. Nitrate leaching in coniferous forest ecosystems: the European fieldscale manipulation experiments NITREX and EXMAN. Global Biogeochemical Cycles 11, 617–626.

Tietema, A., 1998. Microbial carbon and nitrogen dynamics in coniferous forest floor material collected along a European nitrogen deposition gradient. Forest Ecology and Management 101, 29–36.

Vanmechelen, L., Groenemans, R. and Van Ranst, E. (1997) Forest soil conditions in Europe. Results of a large scale soil survey Technical Report. EC, UN/ECE, Ministry of the Flemish Community, Brussels, Geneva, 260 pp.

von Zezschwitz, E., 1985. Qualitätsänderungen des Waldhumus. Forstw. Cbl. 104, 205–220.

Wilson, E.J., Emmett, B.A., 1998. Factors influencing nitrogen saturation in forest ecosystems: advances in our understanding since the mid 1980's. In: Langan, S.J. and Wilson, M.J. (Eds.) The Impact of Nitrogen Deposition on Natural and Semi-Natural Ecosystems. Chapman and Hall.