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Title

Assessing the risk of N leaching from forest soils across a steep N deposition gradient in Sweden

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Abstract

Nitrogen leaching from boreal and temporal forests, where normally most of the nitrogen is retained, has the potential to increase acidification of soil and water and eutrophication of the Baltic Sea. In parts of Sweden, where the nitrogen deposition has been intermediate to high during recent decades, there are indications that the soils are close to nitrogen saturation. In this study, four different approaches were used to assess the risk of nitrogen leaching from forest soils in different parts of Sweden. Nitrate concentrations in soil water and C:N ratios in the humus layer where interpreted, together with model results from mass balance calculations and detailed dynamic modelling. All four approaches pointed at a risk of nitrogen leaching from forest soils in southern Sweden. However, there was a substantial variation on a local scale. Basing the assessment on four different approaches makes the assessment robust.

Capsule

Modelling approaches and environmental monitoring data indicate a risk of elevated N leaching from forest soils in southern Sweden.

Key words

nitrogen leaching, forest, nitrogen retention, modelling, Sweden

1 Introduction

Northern forest ecosystems are generally nitrogen (N) limited (Tamm, 1991). In an N limited forest ecosystem, events with increased N leaching are normally induced by disturbances, such as clear-cutting (Pardo et al., 1995; Hermann et al., 2001; Akselsson et al., 2004; Gundersen et al., 2006), storm fellings (S. Hellsten et al., manuscript) or drainage (Lundin and Bergquist 1990; Lundin, 1999). In areas with high N deposition the retention capacity may, however, be exceeded, and substantially increased N leaching may occur even from undisturbed growing forests (Aber et al., 1989). This is common in central parts of Europe (Gundersen et al., 2006). Maintained N retention is important since elevated N leaching from forest ecosystems would result in a contribution to eutrophication of lakes and oceans, increased acidification of soils and waters and a risk of elevated nitrate concentrations in ground water (Cowling et al., 2001).

In southern Sweden the N deposition is much lower than in central Europe, but still many times higher than the deposition in remote areas almost not affected by N deposition, e.g. the northernmost parts of Sweden (Fig. 1). Although there are no signs of large-scale N leaching from growing forests in Sweden, there is an obvious risk that the N load is close to the retention capacity in parts of the country. The risk may be increased by climate change (e.g. van Breemen et al., 1998). Since forest is the dominant land cover in Sweden, even a relatively small increase in the rate of N leaching from forest soils could have a substantial effect on the total amount of N leaching from forest soils. Assessments of the risk of N leaching from forest soils are important for policy decisions about N emission reductions and forest management practice. The aim of this study was to identify risk areas of N leaching from forest ecosystems at a regional level in Sweden, based on different approaches of environmental monitoring and modelling. The results from the different approaches are discussed and risk areas are suggested, aimed at being a basis for policy decisions about N emission reductions and forest management methods such as N fertilization, removal of forest fuels and methods for regeneration felling.

[FIGURE 1]

2 Materials and methods

2.1 Study area

Sweden is located between the latitudes 55ºN and 69ºN, and therefore the climate varies considerably throughout the country. The transition from temperate to boreal climate is at around 60ºN. In most parts of Sweden precipitation ranges from 600 to 900 mm y^{-1}, but along the west coast it is up 1300 mm and in the mountains in the northwest it can be as high as 2000 mm (Raab and Vedin, 1995). The mean temperature in winter varies between 0ºC in the south and -16ºC in the north. The corresponding values for the summer are 16 and 8ºC (Raab and Vedin, 1995). The N deposition in Sweden ranges over a wide interval, from about 2 kg per hectare and year in the north, to about 15 kg in the southwest (Fig. 1). In the north the deposition is close to the hemispheric background deposition, whereas the deposition in the south is strongly affected by the local and long-range transported N emissions mainly from agricultural land and traffic.

The bedrock in Sweden consists largely of different kinds of igneous rocks, such as granite. Gneisses are common in the southwestern parts of Sweden and sedimentary bedrock is found in some parts of the country. The dominant type of soil is Podzol (according to the FAO/UNESCO soil classification system), and the most common soil texture is sandy till. Ditched organic forest soil accounts for 7% of the managed forest area (Hånell, 1990).

The coniferous tree species Norway Spruce (*Picea abies* (L.) H. Karst.) and Scots Pine (*Pinus sylvestris* L.) are dominant in Swedish forests. Spruce forests cover 27% of the forested area and the corresponding fraction for pine forests is 39% (Swedish University of Agricultural Sciences, 2008). Spruce is the dominant coniferous species in the southern part of Sweden, whereas pine is more common than spruce in the northern part of Sweden. Birch is the most common deciduous species (*Betula pubescens* Ehrh. and *Betula pendula* Roth), while European beech (*Fagus sylvatica* L.), trembling aspen *(Populus tremula L.)* and pedunculate oak (*Quercus robur* L.) cover smaller areas. The dominant method for regeneration felling is clear-cutting (Stokland et al., 2003). Traditional forestry in Sweden involves the harvest of stems only. However, during recent decades whole-tree harvesting, in which branches, tops and needles are removed, has become more common. In 2007, the extent of removal of branches, tops and needles was approximately 38 % of the harvested area, based on reports from the forest owners (Swedish Forest Agency, 2008). In the last years, also stump harvesting is an increasing activity in forestry.

2.2 Methodological overview - Compilation of four approaches

Data from four approaches were compiled and analysed with respect to the risk of N leaching:

- Mass balance modelling on a large numbers of sites in Sweden for estimation of annual N accumulation (Akselsson et al., 2008).
- Measured nitrate (NO_3-N) concentrations in soil water from the Swedish Throughfall Monitoring Network (Hallgren Larsson et al., 1995).
- Measured C:N ratios in the organic layer from the Swedish National Forest Soil Inventory monitored by the Swedish University of Agricultural Sciences (Hägglund, 1985).
- Dynamic modelling with the ForSAFE-VEG model (Wallman et al., 2005; Belyazid et al., 2006), simulating future N dynamics in forest soils for three sites representing different parts of Sweden.

In mass balance calculations of N (Akselsson et al., 2008), net inputs (deposition and fixation) are weighed against net outputs (harvest losses, leaching and denitrification). It gives the accumulation or net losses of N. It does not include the present N status of the soil, but still provides an indication of the N sustainability of a system. High accumulation indicates a risk of N leaching and ground vegetation changes whereas net losses mean strengthened N limitation and a risk of negative effects on tree growth. Mass balance calculations capture the gradient of the N status, whereas it is difficult to relate the accumulation rates to an actual risk of N leaching.

Nitrate concentrations in soil water in northern forest ecosystems are generally low, since the forests are N limited and take up all available N. Elevated nitrate concentrations indicate an excess of N. The Swedish Throughfall Monitoring Network has long time series of element concentrations, e.g. nitrate, in soil water at 50 cm depth in the mineral soil, on many sites covering the whole country. These time series can be used for identifying areas where nitrate concentrations are elevated, indicating a risk of large-scale N leaching.

C:N ratios in the organic layer have been frequently used to identify risk areas of N leaching, based on a correlation between the C:N ratio and nitrate leaching in European forests (Gundersen et al., 1998). In the Swedish National Forest Soil Inventory, C and N in the organic layer have been measured on several thousand sites all over Sweden. The C:N ratios on these sites can be useful in the identification of risk areas for N leaching.

The dynamic model ForSAFE-VEG (Wallman et al., 2005; Belyazid et al., 2006) includes process-based descriptions of weathering, soil chemistry, decomposition, tree growth and ground vegetation. The model has been run on numerous sites in

Europe (Belyazid et al., 2006; Sverdrup et al., 2007), and is being used to develop estimates of critical loads of N based on biological impacts of N deposition (Belyazid et al., 2009). Present development efforts are focused on improving N processes and developing the VEG part for calculations of critical load of N with respect to changes in ground vegetation. The model result can be used as a basis for discussions regarding N leaching for different climate, forestry and deposition scenarios.

2.3 Modelling N accumulation with the mass balance model

N accumulation has been calculated on 14550 coniferous sites from Swedish National Inventory on Forests in an earlier study (Akselsson et al., 2008). The accumulation in soil (Δ) was calculated as:

$$\Delta = \text{Deposition} + \text{Fixation} - \text{Harvesting} - \text{Leaching}$$

Denitrification was neglected since it can be expected to be very small in well-drained forests. Whereas current rates, or approximations of current rates, can be used for the deposition and leaching terms, the harvesting term must be regarded in the perspective of a whole forest rotation. Thus, the results of the calculations give the annual net change as an average for a forest rotation, provided that the other terms are constant over time.

The best available regional-scaled data was incorporated into the input database for each of the four input parameters and mass balance calculations were then made for all the sites (Akselsson and Westling, 2005; Akselsson et al., 2008). Deposition was derived from the Swedish MATCH model in the 5×5 km resolution (Langner et al., 1996) and N fixation was set to a constant value, 1.5 kg ha^{-1} y^{-1}, based on a study in northern Sweden (DeLuca et al., 2002). Harvest losses of N were estimated based on growth data from the Swedish National Forest Inventory together with N concentrations in different trees (Egnell et al., 1998; Jacobson and Mattson, 1998). The variation for N concentration in runoff water from growing forests in Sweden is small, due to high N retention. This justifies the use of one average value for southern Sweden and one value for central and northern Sweden. For central and northern Sweden N leaching was calculated based on an empirical relationship including runoff (Akselsson and Westling, 2005). In southern Sweden N concentrations in surface water from 23 catchments were combined with runoff data. The elevated concentrations after clear-cutting were included according to methodologies used in earlier studies (Akselsson and Westling, 2005).

2.4 Monitoring data of nitrate in soil water

Soil water chemistry is presently measured on 64 forest sites within the Swedish Throughfall Monitoring Network (Hallgren Larsson et al., 1995), along with measurements of deposition of S, N and base cations. In addition there are several sites where measurements have been performed until recent years. The first measurements started in 1985 in the southern part of Sweden. Soil water concentrations in the mineral soil at 50 cm depth have been sampled, using lysimetres, three times a year, during the vegetation period as well as before and after. Concentrations of e.g. sulphate, hydrogen ions, chloride, nitrate, ammonium, aluminium and base cations have been analysed in the soil water.

In the present study soil water data from 88 sites were compiled, 64 of which are presently running, and 24 are ended, but have been run until December 2006 or later. In some cases it has not been possible to derive water, which has led to missing values in the data series. In other cases the soil water amounts were very small due to difficulties in deriving water, leading to large uncertainties in the measured concentrations. Measurements based on sample sizes less than 50 mg l^{-1} (3% of the samples) were excluded from the analysis in this study due to large uncertainties.

The sites were divided into seven different nitrate concentration classes based on both frequency of elevated concentrations and size of the elevations (Table 1). On 24 of the sites only measurements before 2005 were used, since these sites were affected by a storm in January 2005. In some cases there were obvious effects of the storm on the nitrate leaching whereas on other sites there were only suspicions about storm effects. In two cases the forest was clear-cut in 2000, and in those cases only the concentrations before 2000 where included, to avoid the clear-cut effect. The storm- and clear-cut effects will be evaluated in separate studies, and were not included here since this study refers to undisturbed growing forests. On most of the sites the measurements started in the end of the 1980's or in the 1990's. On four sites the measurements started after year 2000.

[TABLE 1]

2.5 Monitoring data of C:N in the organic layer

Within the Swedish National Forest Soil Inventory (Hägglund, 1985), managed by the Swedish University of Agricultural Sciences in Uppsala, C and N concentrations in the soil organic layer have been measured on 5537 sites between 1993 and 1998. In this study, the C:N ratios for these sites were used. Ratios below 25 indicate an increased risk of N leaching, based on empirical studies (Gundersen et al., 1998) and thus the frequency of sites with ratios below 25 in different regions were estimated. Furthermore the variation in ratios was related to tree species.

2.6 Modelled N dynamics with the dynamic model ForSAFE-VEG

The ForSAFE-VEG model (Wallman et al., 2005; Belyazid et al., 2006) is a dynamic and mechanistic ecosystem model, handling weathering, soil chemistry, decomposition, tree growth, ground vegetation and hydrology. The model can be used for simulating effects of climate change, forestry and changed deposition on acidification, N cycling, tree growth and ground vegetation. A first attempt to use the model on a national level has been done, where 16 sites all over Sweden were modeled (Belyazid et al., 2006). The focus in that study was on base cations and acidification. Since then the descriptions of N cycling in the model have been improved, i.e. through better differentiation between different N species and better description of N reactions in anaerobic conditions. The work on refining N processes in the model is still on-going. In this study, N leaching on three of the 16 sites has been modeled, Brattfors, Höka and Söstared, which are all pine sites. The three sites are representing different N deposition regions. The modelling was performed for two forest rotations, using input data from earlier studies (Belyazid et al., 2006).

2.7 Weighing together the four different approaches

Sweden was divided into three different N status regions based on the N accumulation map. Statistics on measured nitrate concentrations in soil water, measured C:N ratios in the organic layer and modelled N accumulation were calculated for each region. A t-test assuming equal variances was used to test if there were significant differences between the regions with respect to N accumulation and C:N ratios. The results were compared with the results on nitrate concentrations in soil water from the dynamic modelling, where one site from each region was modelled.

3 Results

The results from the four different approaches all showed a gradient with an increased N status from the north to the southwest (Figs 2-6, Tables 2-5). There was a significant difference in N accumulation between the different regions, both with respect to N accumulation in spruce forests and N accumulation in pine forests ($p<0.001$). In region 1, covering northern and central Sweden, the N accumulation estimated from the nitrogen balance modelling was generally below 4 kg ha^{-1} y^{-1} (Fig. 2), except for some areas in the south where it was somewhat higher. Region 2 and 3 showed a clear gradient with increasing N accumulation from northeast to southwest. In region 2 the accumulation was generally between 4 and 8 kg ha^{-1} y^{-1}. In region 3 the N accumulation was above 8 kg ha^{-1} y^{-1} on most of the sites. The accumulation was higher in pine forests than in spruce forests (Table 2). Although the variation on a local scale was considerable, the strong large-scale gradient overshadowed much of the local variation.

[FIGURE 2]

[TABLE 2]

Nitrate concentrations in the soil water were very low on many sites (Fig. 3, Table 3). Sites with very low concentrations were abundant in all regions (Fig. 3; Fig. 4(a), 4(b) and 4(d)). Most of the sites with elevated concentrations, temporarily or chronically, were situated in region 3 (Fig. 3; Figs 4(e) and 4(f); Table 3). There were, however a number of sites with elevated concentrations also in region 2 (Fig. 3; Fig. 4(c); Table 3).

[FIGURE 3]

[TABLE 3]

[FIGURE 4]

The C:N ratios varied substantially on a local scale (Fig. 5). There was, however, a gradient with the highest fraction of sites with C:N below 25 in region 3 and the lowest fraction in region 1 (Table 4-5). This gradient can be seen both in pine forests and in spruce forests. The difference in C:N between region 1 and 3 was significant both for spruce ($p<0.001$) and pine ($p<0.01$). There were strong tendencies towards differences between region 2 and 3 ($p=0.06$ for spruce and $p=0.08$ for pine), however not significant. The statistical analysis for region 1 and 2 showed no significant differences or tendencies ($p=0.28$ for spruce and $p=0.43$ for pine). Within region 1 the frequency of sites with a C:N ratio below 25 was higher in the southern part than in the northern part. The C:N ratios were generally higher in pine forests than in spruce forests.

The NO_3 concentrations in the soil water, as modelled with ForSAFE-VEG, showed increases after clear-cutting on all sites (Fig. 6). The increase was largest in Söstared in region 3, and smallest in Brattfors in region 1. In Brattfors and Höka the concentrations returned to normal, i.e. very low levels, after 20 years. Also in

Söstared the concentrations decreased, but the concentrations were elevated during the whole forest rotation period.

[FIGURE 5]

[TABLE 4]

[TABLE 5]

[FIGURE 6]

4 Discussion

The results from the four different approaches all showed a gradient with higher N status in the southern part of Sweden than in the north. In region 1, corresponding to the northern and central part of Sweden, the risk of elevated N leaching was estimated to be small. The accumulation of N was low, the nitrate concentration in soil water was generally very low and the C:N ratios were generally above 25. The dynamic modelling in Brattfors showed small increases in soil water nitrate concentrations after clear-cutting, but the concentrations then returned to normal, very low levels. In the southern part of region 1 the frequency of sites with C:N ratios < 25 was somewhat higher than in the northern part, and the N accumulation was somewhat higher, but there were no signs of elevated concentrations in the soil water, and thus the overall conclusion about a low risk of elevated N leaching remains.

In region 2, i.e. the southern part of Sweden except the most southwestern part, the N accumulation in the forest ecosystems was higher, and there was a gradient with higher accumulation to the southwest. The frequency of C:N ratios below 25 was about the same as in the southern part of region 1. In the southwestern part of region 2 there were a few sites with elevated nitrate concentrations in soil water. The dynamic modelling in Höka showed a similar pattern as for Brattfors in the northern region 1, but the nitrate concentration after clear-cutting was higher and the elevated nitrate concentrations persisted for a longer time. Hence, region 2 was assessed as a risk area for elevated N leaching, although the risk was relatively small. The risk was deemed to be highest in the southwestern part of region 2.

In region 3, i.e the southwestern part of Sweden, the N accumulation in the forest ecosystems was generally above 8 kg ha^{-1} y^{-1} and the C:N ratios in the organic soil layer were lower than in the rest of Sweden. The nitrate concentrations in soil water were elevated on several of the sites. The dynamic modelling in Söstared showed substantially elevated soil water nitrate concentrations after clear-cutting, and the elevation persisted during the whole forest rotation, in contrast to the results in Höka and Brattfors. Region 3 was, based on these results, assessed as an area with considerable risk of elevated N leaching.

Although there were clear differences between the three regions, the variation within a region was also large, which was evident for the C:N ratios and the nitrate concentrations. The risk assessments above refer to the general conditions for a specific region, but on a local scale the risk can differ substantially from the average risk of the region to which it belongs. Thus site characteristics are important in estimating the risk of nitrate leaching on a local scale.

The risk analysis can be used as a basis for policy making, e.g in abatement strategies of N emission reductions, and in advising the forest sector about N fertilization, harvesting of forest fuels and methods for clear cuttings. However, the risk analysis is based merely on the risk of N leaching. In region 1, which was assessed as a low risk area, the main risk of damage from N deposition is change in ground vegetation distribution (Nordin et al., 2005). Furthermore, the risk analysis presented in this study was based on current conditions. A future intensified forest management practice, with increased N fertilization in a changing climate, may affect the risk of leaching.

All approaches are associated with strengths and weaknesses. Using a single one of the four different approaches would lead to large uncertainties, but by combining the four approaches, as was done in this study, the strengths of the different approaches are combined, and the uncertainties in the final assessments become smaller. The strength with the monitoring data is that it is real data, which shows the actual status in the forest. The strength with the modelled data is that it is possible to scale up, both spatially, with the mass balance model, and temporally, with the dynamic model.

Measuring nitrate concentrations in the soil water is the only method where nitrate leaching, or at least the first step of nitrate leaching, is actually measured. Thus this is a very important dataset and these measurements should be continued in order to keep track of changes in the soil water quality. The C:N ratios in the organic soil layer should be seen only as a first rough method to estimate the risk of leaching. The method is applicable mainly on an European level, to distinguish between high risk areas (with low C:N ratios) and low risk areas (with high C:N ratios) (Gundersen, 1998). However, as pointed out in Gundersen (1998), there is a large variation in the span 25-30, which applies for southern Sweden, with soil water nitrogen concentrations ranging between 0 and 20 mg l^{-1}. This indicates that there are other important factors that are determinant for nitrate leaching. Recent reviews have suggested differences in microbial activity as a possible explanation for the difference in nitrate leaching between sites (Booth et al., 2005; Emmett, 2007). Furthermore, future climate change may greatly affect N processes in soils due to effects on e.g. soil hydrology, soil organisms and plant growth, confounding the presumed relationship between C:N ratio and N leaching.

With the mass balance calculations, the forest ecosystem N status gradient is captured, and scenario calculations can be done for e.g. different deposition and forest management scenarios. However, the quantification of the relation between

N accumulation and the actual risk of leaching is uncertain. The dynamic modelling approach, on the other hand, is an effort to analyse the effects in a holistic way, by including all important ecosystem processes and feedbacks. It is an important tool for investigating the integrated effects of climate, forestry and deposition on N dynamics. However, at this stage of the model development, the dynamic modelling should only be used to assess the N dynamics on a few, well investigated sites and to compare the N responses of different climate, deposition and forestry scenarios, rather than to estimate the risk of leaching on a regional or national scale.

Combining modelling and experimental approaches is important for increased process understanding. By running dynamic models in well investigated sites, such as experimental or environmental monitoring sites, the process understanding can be increased and the dynamic models can be continuously improved. Two of the sites modelled with ForSAFE-VEG are included in the 88 Swedish Throughfall Monitoring Network sites investigated in this study, Höka and Söstared. Höka, the site in region 2, shows very low soil water nitrate concentration in the measurements, which is similar to the model results. The modelled soil water nitrate concentrations are elevated for some time after clear-cutting, but then returns to low levels. The soil water nitrate concentrations in the measurements in Söstared are also very low. However, the model results show elevated soil water nitrate concentrations after a simulated clear cutting during the whole subsequent rotation period, with a peak just after clear-cutting. In-depth analysis of the difference between the modelled and measured soil water nitrate concentrations in Söstared can be one of the keys to increased understanding of soil N retention processes. The concentrations after clear-cutting according to the modelling are reasonable, as compared with measured concentrations. In the modelled clear-cut in the 21st century, the maximum soil water nitrate concentration was 0.2 mg l^{-1} in the northern site, 3.6 mg l^{-1} in the middle site and 8.0 mg l^{-1} in the southwestern site. Measurements on 24 sites in southern Sweden showed concentrations after clear-cutting between 0.2 and 5.7 mg l^{-1} (Akselsson et al., 2004), i.e. the same magnitude as the modelled concentrations. The duration of the leaching event after clear-cutting was, however, overestimated by the model on all three sites due to the fact that uptake by understorey vegetation is not included in the model at this stage.

Future climate scenarios show large changes in temperature and precipitation in the near future (Houghton et al., 2001). This will change the conditions in forest soils, through the impact on important ecosystem processes such as decomposition, weathering, percolation and tree growth. Furthermore, forestry will most likely be intensified to meet the increasing demand of biofuels. N fertilization may become more widespread. Of the different methods applied in this study, the dynamic modelling approach with ForSAFE-VEG is the only one that can be used for assessing effects of climate change. The climate scenario adopted gradually diverges from the control scenario of no climate change, starting from 2010. The effects of climate change on N leaching are therefore discussed for the second clear-cut events shown in Fig. 6. At the three sites, clear-cutting events trigger a peak in NO_3 leaching. The duration and magnitude of leaching is affected by the climatic conditions, as well as by the atmospheric deposition, the harvest intensity and the site conditions. At the northern site Brattfors, a change in climate will result in a lower leaching magnitude with a shorter duration following clear-cutting. Higher temperatures in the future will contribute more to increasing forest growth rates, and subsequently nitrogen uptake by the roots, than to the release of N through decomposition and mineralization. At the central site, Höka, the opposite will occur. The future change in climate will release large amounts of accumulated N in the soil, and the marginal increase in forest growth rates due to higher temperatures will not suffice for the roots to take up all the released N. Finally, at the southern site Söstared, climate change will lead to higher N leaching in the short term following the clear-cut, but to lower N leaching later on in the rotation period, according to the model results.

5 Conclusions

There is a risk of increased nitrate leaching from forest soils in southern Sweden, with the highest risk in the southwestern part. The risk in central and northern Sweden seems to be small under current conditions. However, the risk of elevated leaching varies substantially on a local scale, thus it is important to include stand factors in the risk assessment on a local scale.

The monitoring and modelling approaches are associated with different strengths and weaknesses. Basing the assessment on four different approaches, as was done in this study, makes it more robust than if only one single approach was used. Furthermore, the different approaches have different resolution in time and space, and through the combination of the methods the best possible resolution in both time and space can be obtained. There are still knowledge gaps about N cycling and how it is affected by climate change. Experimental approaches and environmental monitoring data are important to improve the knowledge. Dynamic modelling in well investigated sites is an appropriate way for increased process understanding and improved modelling of the N cycling.

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Tables

Table 1. Criteria for division into nitrate concentration classes.

Class	Description	Criteria
1	Very low concentrations	Max. conc. <0.01 mg l^{-1}
2		Max. conc. betw. 0.01 & 0.1 mg l^{-1}
3		One conc. >0.1 but <0.5 mg l^{-1}
4		Several conc. >0.1 but < 0.5 mg l^{-1}
5		One conc. > 0.5 mg l^{-1}
6		At least two conc. > 0.5 mg l^{-1}
7	Substantially elevated concentrations	Mean conc. >1 mg l^{-1}

Table 2. Statistics for the N accumulation (kg ha^{-1} y^{-1}) estimated from the nitrogen balance modelling in the three areas, for spruce and pine separately.

	Spruce			Pine		
Region	Median	95-perc.	5-perc.	Median	95-perc.	5-perc.
1	2.5	4.0	1.2	2.6	5.3	1.1
2	6.2	7.8	4.4	7.2	9.5	5.5
3	8.5	10.0	6.7	11.1	13.1	9.0

Table 3. Percentage of sites with soil water N concentration classes 6 and 7 (see Table 1).

Region	Class 7	Class 6	Class 7+6
1	0	3	3
2	3	12	15
3	20	20	40

Table 4. Statistics for the C:N ratio in the organic layer in the three areas for spruce.

Region	Median	95-perc.	5-perc.	Percentage with C:N<25 (%)
1	29	43	16	29
2	26	34	17	42
3	25	32	17	48

Table 5. Statistics for the C:N ratio in the organic layer in the three areas for pine.

Region	Median	95-perc.	5-perc.	Percentage with C:N<25 (%)
1	36	55	21	12
2	32	45	21	16
3	28	40	18	36

Figures

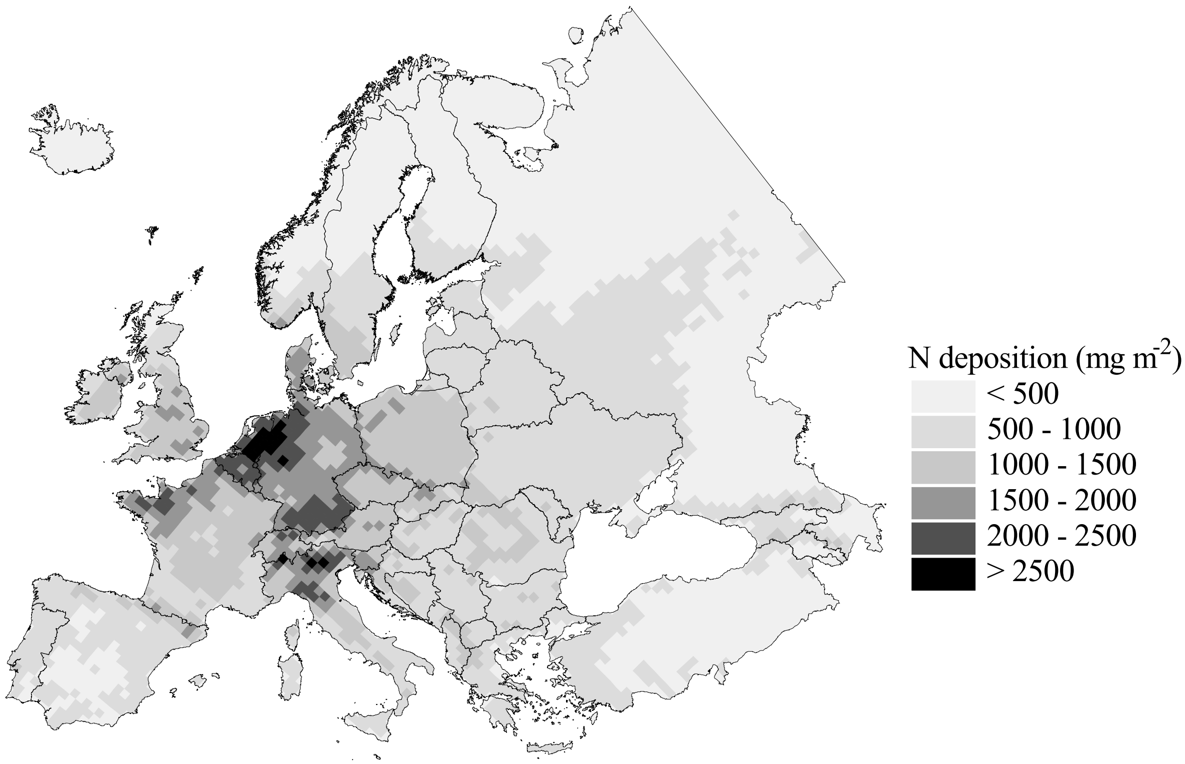

Fig. 1. N deposition in Europe in year 2000 (mixed landuse) according to the EMEP model.

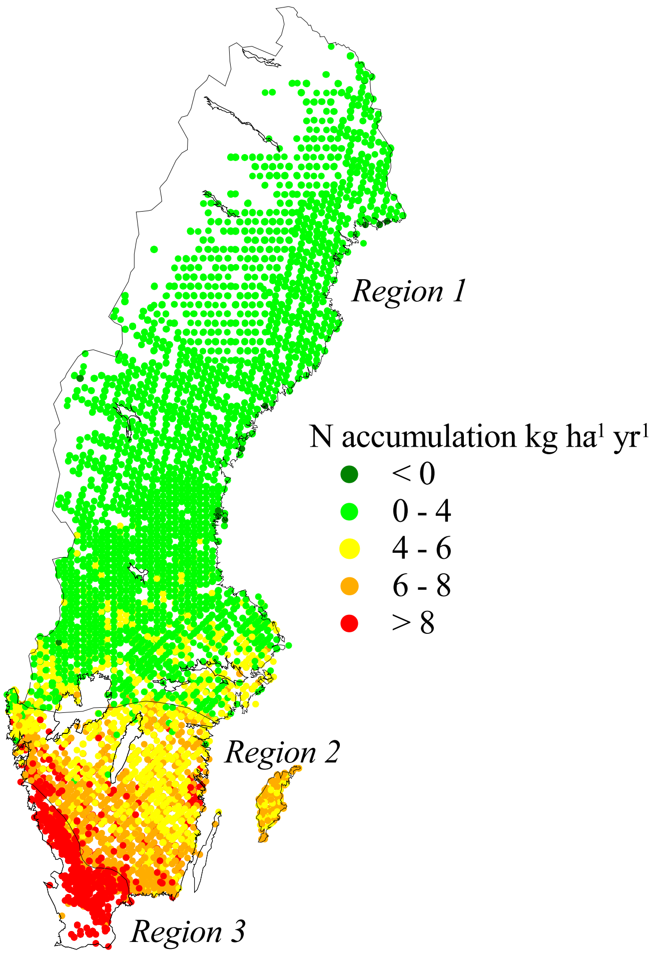

Fig. 2. N accumulation estimated from the nitrogen balance modelling in 5641 spruce sites and 6749 pine sites in Sweden. Based on the N accumulation, Sweden was divided in three regions.

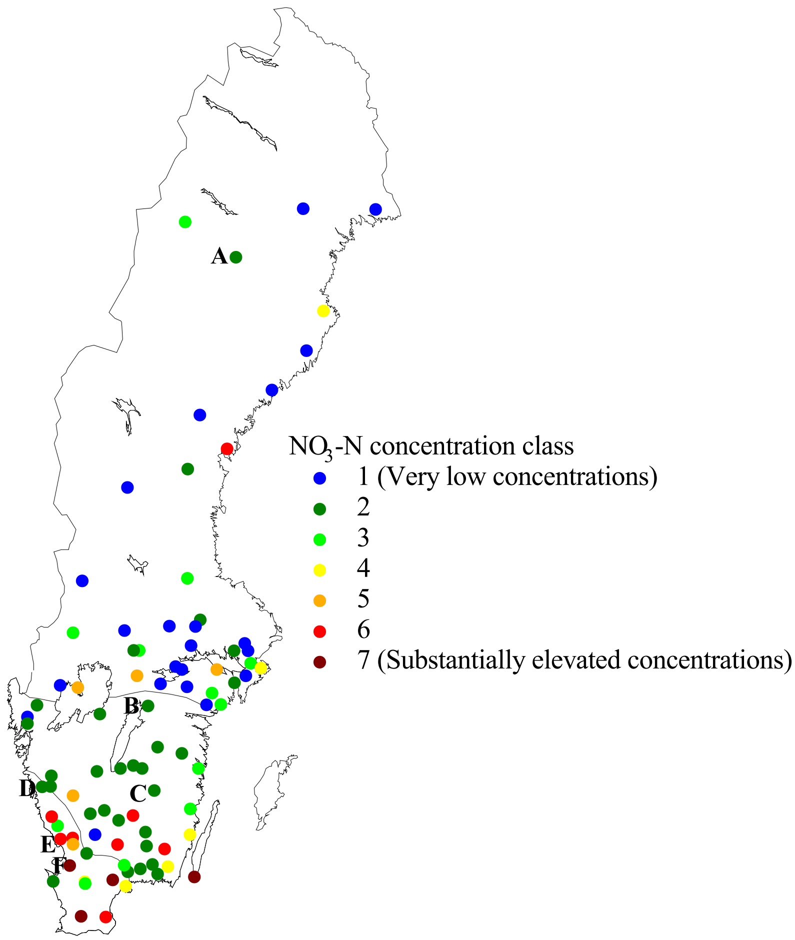

Fig. 3. 88 sites in the Swedish Throughfall Monitoring Network divided into seven classes with different nitrate (NO_3-N) concentration according to Table 1. Graphs for the sites A-F are shown in Figure 4.

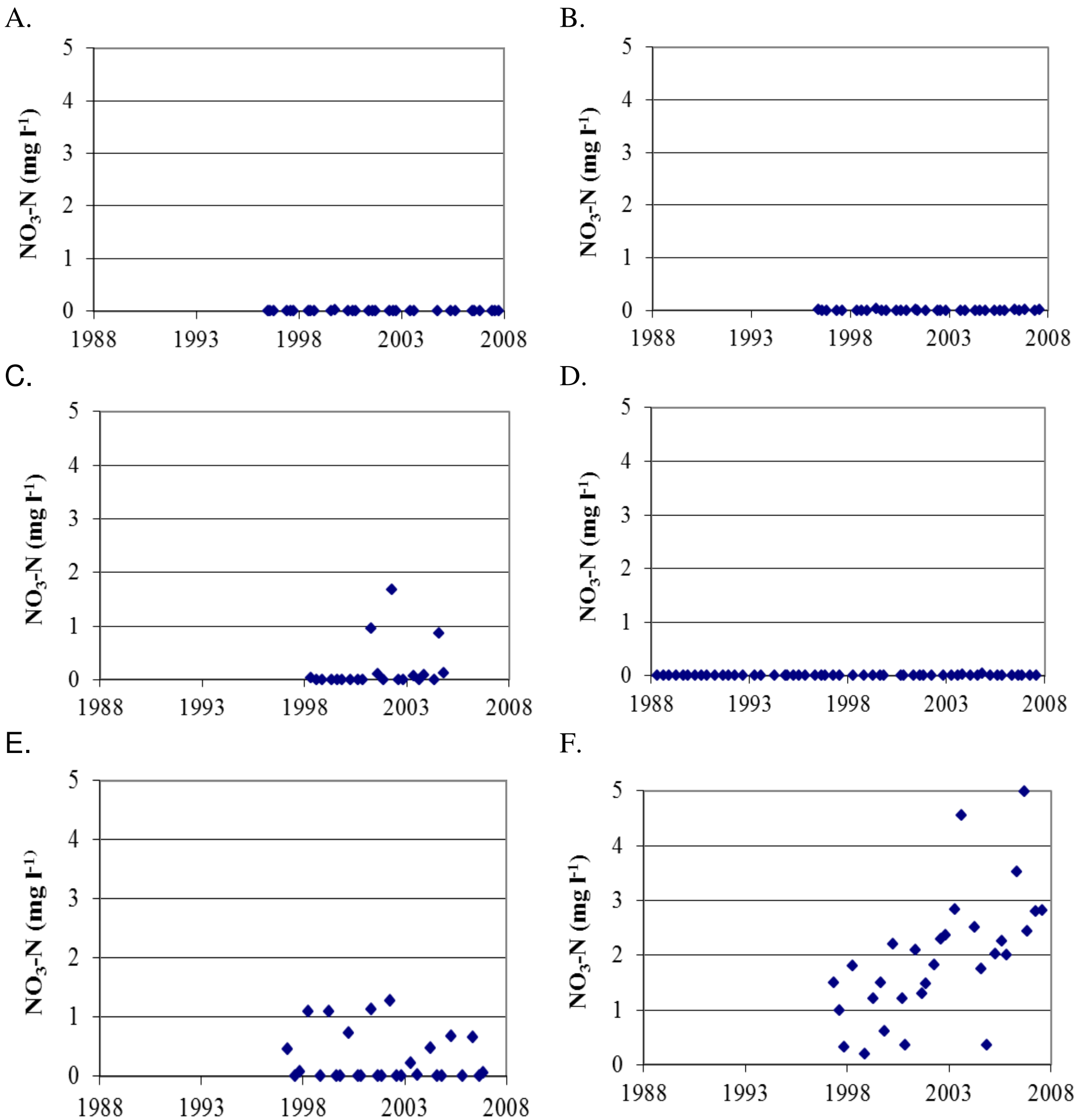

Fig. 4. Nitrate (NO_3-N) concentrations in soil water in Högbränna, Norway spruce, 92 years (a), Höka, Scots pine, 72 years (b), Asa, Norway spruce, 46 years (c), Söstared, Scots pine, 84 years (d), Fastarp, Norway spruce, 71 years (e) and Vallåsen, Norway spruce, 70 years (f). The location of the sites is shown in Figure 3. The age of the trees refers to 2007, the year from which the last data in this study derives.

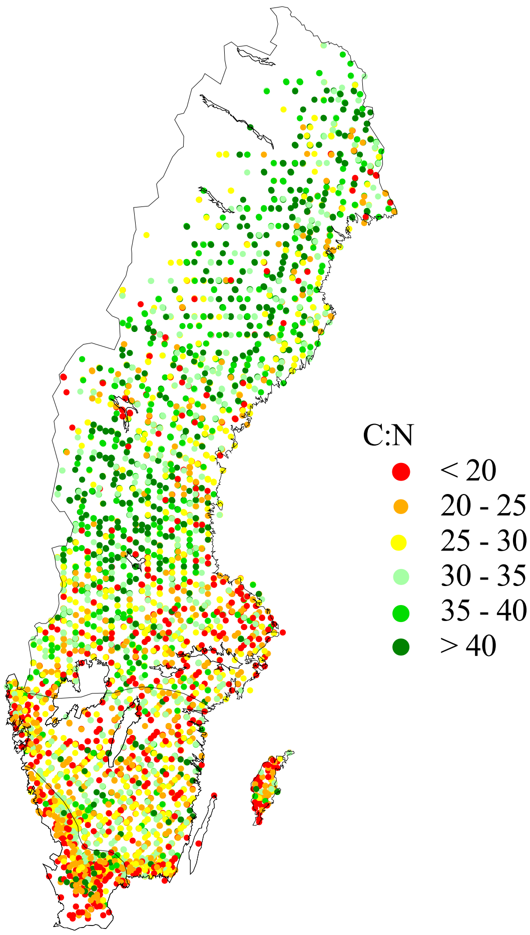

Fig. 5. C:N ratio in the organic layer in spruce and pine forests.

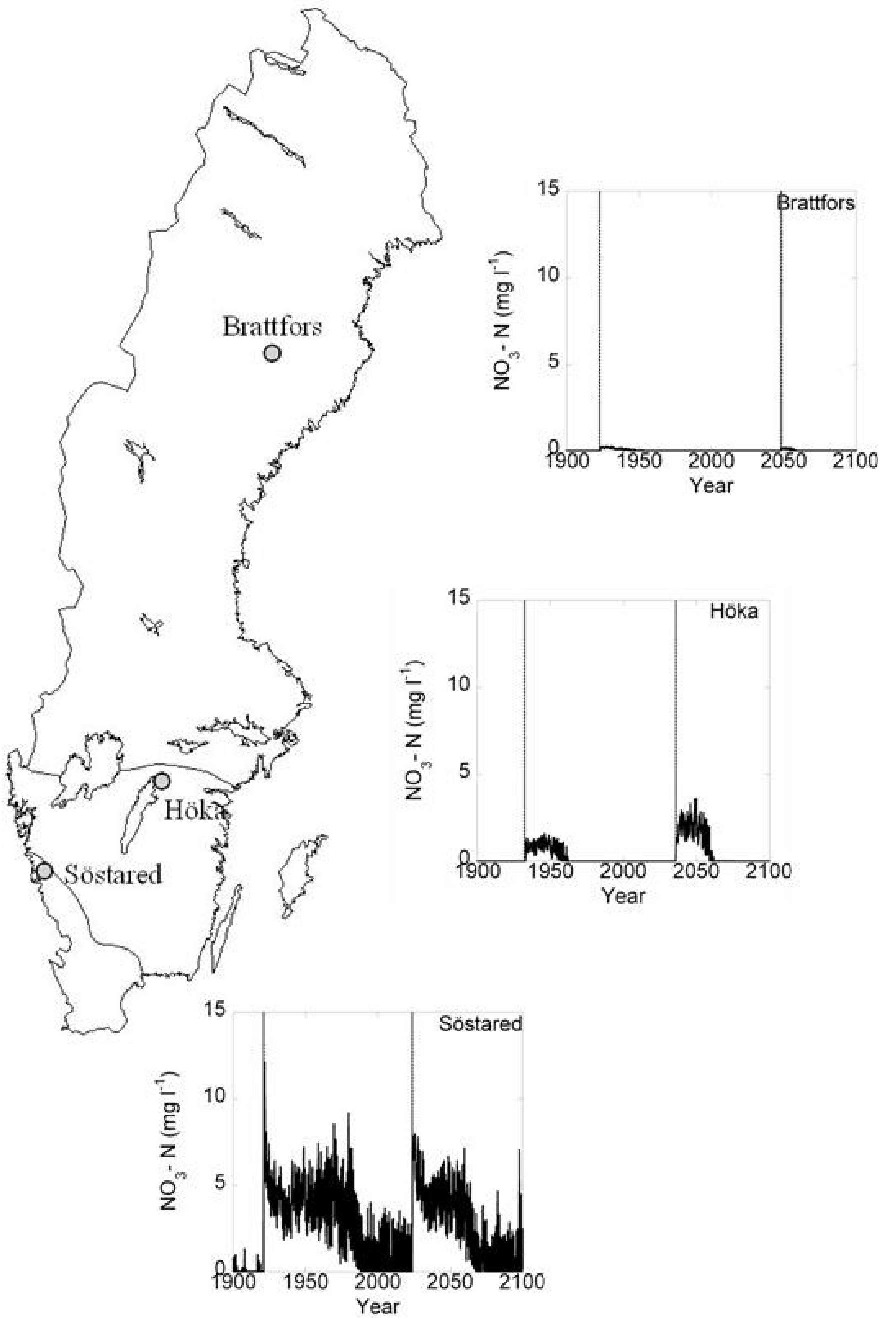

Fig. 6. Concentration of nitrate (NO_3-N) in soil water (µekv l^{-1}) in pine forests in Brattfors, Höka and Söstared 1900-2100 as modeled with the ForSAFE-VEG model. Vertical lines are clearcuts.