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

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1 Abstract

2 Nitrogen leaching from boreal and temporal forests, where normally most

3 of the nitrogen is retained, has the potential to increase acidification of soil and

4 water and eutrophication of the Baltic Sea. In parts of Sweden, where the nitrogen

5 deposition has been intermediate to high during recent decades, there

6 are indications that the soils are close to nitrogen saturation. In this

7 study, four different approaches were used to assess the risk of

8 nitrogen leaching from forest soils in different parts of Sweden.

9 Nitrate concentrations in soil water and C:N ratios in the humus layer

10 where interpreted, together with model results from mass balance

11 calculations and detailed dynamic modelling. All four approaches pointed

12 at a risk of nitrogen leaching from forest soils in southern Sweden.

13 However, there was a substantial variation on a local scale. Basing the

14 assessment on four different approaches makes the assessment robust.

15

16 Capsule

17 Modelling approaches and environmental monitoring data indicate a risk of

18 elevated N leaching from forest soils in southern Sweden.

19

20 Key words

21 nitrogen leaching, forest, nitrogen retention, modelling, Sweden

22

23

1   1 Introduction

2   Northern forest ecosystems are generally nitrogen (N) limited (Tamm, 1991). In an

3   N limited forest ecosystem, events with increased N leaching are normally induced

4   by disturbances, such as clear-cutting (Pardo et al., 1995; Hermann et al., 2001;

5   Akselsson et al., 2004; Gundersen et al., 2006), storm fellings (S. Hellsten et al.,

6   manuscript) or drainage (Lundin and Bergquist 1990; Lundin, 1999). In areas with

7   high N deposition the retention capacity may, however, be exceeded, and

8   substantially increased N leaching may occur even from undisturbed growing

9   forests (Aber et al., 1989). This is common in central parts of Europe (Gundersen

10   et al., 2006). Maintained N retention is important since elevated N leaching from

11   forest ecosystems would result in a contribution to eutrophication of lakes and

12   oceans, increased acidification of soils and waters and a risk of elevated nitrate

13   concentrations in ground water (Cowling et al., 2001).

14

15   In southern Sweden the N deposition is much lower than in central Europe, but still

16   many times higher than the deposition in remote areas almost not affected by N

17   deposition, e.g. the northernmost parts of Sweden (Fig. 1). Although there are no

18   signs of large-scale N leaching from growing forests in Sweden, there is an

19   obvious risk that the N load is close to the retention capacity in parts of the country.

20   The risk may be increased by climate change (e.g. van Breemen et al., 1998).

21   Since forest is the dominant land cover in Sweden, even a relatively small increase

22   in the rate of N leaching from forest soils could have a substantial effect on the

23   total amount of N leaching from forest soils. Assessments of the risk of N leaching

1 from forest soils are important for policy decisions about N emission reductions and

2 forest management practice. The aim of this study was to identify risk areas of N

3 leaching from forest ecosystems at a regional level in Sweden, based on different

4 approaches of environmental monitoring and modelling. The results from the

5 different approaches are discussed and risk areas are suggested, aimed at being a

6 basis for policy decisions about N emission reductions and forest management

7 methods such as N fertilization, removal of forest fuels and methods for

8 regeneration felling.

9

10 [FIGURE 1]

11

12 2 Materials and methods

13 2.1 Study area

14 Sweden is located between the latitudes 55ºN and 69ºN, and therefore the climate

15 varies considerably throughout the country. The transition from temperate to boreal

16 climate is at around 60ºN. In most parts of Sweden precipitation ranges from 600 to

17 900 mm y^{-1}, but along the west coast it is up 1300 mm and in the mountains in the

18 northwest it can be as high as 2000 mm (Raab and Vedin, 1995). The mean

19 temperature in winter varies between 0ºC in the south and -16ºC in the north. The

20 corresponding values for the summer are 16 and 8ºC (Raab and Vedin, 1995). The

21 N deposition in Sweden ranges over a wide interval, from about 2 kg per hectare

22 and year in the north, to about 15 kg in the southwest (Fig. 1). In the north the

23 deposition is close to the hemispheric background deposition, whereas the

1   deposition in the south is strongly affected by the local and long-range transported

2   N emissions mainly from agricultural land and traffic.

3

4   The bedrock in Sweden consists largely of different kinds of igneous rocks, such as

5   granite. Gneisses are common in the southwestern parts of Sweden and

6   sedimentary bedrock is found in some parts of the country. The dominant type of

7   soil is Podzol (according to the FAO/UNESCO soil classification system), and the

8   most common soil texture is sandy till. Ditched organic forest soil accounts for 7%

9   of the managed forest area (Hånell, 1990).

10

11   The coniferous tree species Norway Spruce (*Picea abies* (L.) H. Karst.) and Scots

12   Pine (*Pinus sylvestris* L.) are dominant in Swedish forests. Spruce forests cover

13   27% of the forested area and the corresponding fraction for pine forests is 39%

14   (Swedish University of Agricultural Sciences, 2008). Spruce is the dominant

15   coniferous species in the southern part of Sweden, whereas pine is more common

16   than spruce in the northern part of Sweden. Birch is the most common deciduous

17   species (*Betula pubescens* Ehrh. and *Betula pendula* Roth), while European beech

18   (*Fagus sylvatica* L.), trembling aspen *(Populus tremula L.)* and pedunculate oak

19   (*Quercus robur* L.) cover smaller areas. The dominant method for regeneration

20   felling is clear-cutting (Stokland et al., 2003). Traditional forestry in Sweden

21   involves the harvest of stems only. However, during recent decades whole-tree

22   harvesting, in which branches, tops and needles are removed, has become more

23   common. In 2007, the extent of removal of branches, tops and needles was

1   approximately 38 % of the harvested area, based on reports from the forest owners

2   (Swedish Forest Agency, 2008). In the last years, also stump harvesting is an

3   increasing activity in forestry.

4

5   2.2 Methodological overview - Compilation of four approaches

6   Data from four approaches were compiled and analysed with respect to the risk of

7   N leaching:

8

9   •   Mass balance modelling on a large numbers of sites in Sweden for estimation

10   of annual N accumulation (Akselsson et al., 2008).

11   •   Measured nitrate (NO_3-N) concentrations in soil water from the Swedish

12   Throughfall Monitoring Network (Hallgren Larsson et al., 1995).

13   •   Measured C:N ratios in the organic layer from the Swedish National Forest Soil

14   Inventory monitored by the Swedish University of Agricultural Sciences

15   (Hägglund, 1985).

16   •   Dynamic modelling with the ForSAFE-VEG model (Wallman et al., 2005;

17   Belyazid et al., 2006), simulating future N dynamics in forest soils for three sites

18   representing different parts of Sweden.

19

20   In mass balance calculations of N (Akselsson et al., 2008), net inputs (deposition

21   and fixation) are weighed against net outputs (harvest losses, leaching and

22   denitrification). It gives the accumulation or net losses of N. It does not include the

23   present N status of the soil, but still provides an indication of the N sustainability of

24   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

1   Europe (Belyazid et al., 2006; Sverdrup et al., 2007), and is being used to develop

2   estimates of critical loads of N based on biological impacts of N deposition

3   (Belyazid et al., 2009). Present development efforts are focused on improving N

4   processes and developing the VEG part for calculations of critical load of N with

5   respect to changes in ground vegetation. The model result can be used as a basis

6   for discussions regarding N leaching for different climate, forestry and deposition

7   scenarios.

8

9   2.3 Modelling N accumulation with the mass balance model

10   N accumulation has been calculated on 14550 coniferous sites from Swedish

11   National Inventory on Forests in an earlier study (Akselsson et al., 2008). The

12   accumulation in soil (Δ) was calculated as:

13

14   Δ = Deposition + Fixation - Harvesting – Leaching

15

16   Denitrification was neglected since it can be expected to be very small in well-

17   drained forests. Whereas current rates, or approximations of current rates, can be

18   used for the deposition and leaching terms, the harvesting term must be regarded

19   in the perspective of a whole forest rotation. Thus, the results of the calculations

20   give the annual net change as an average for a forest rotation, provided that the

21   other terms are constant over time.

22

1   The best available regional-scaled data was incorporated into the input database

2   for each of the four input parameters and mass balance calculations were then

3   made for all the sites (Akselsson and Westling, 2005; Akselsson et al., 2008).

4   Deposition was derived from the Swedish MATCH model in the 5×5 km resolution

5   (Langner et al., 1996) and N fixation was set to a constant value, 1.5 kg ha^{-1} y^{-1},

6   based on a study in northern Sweden (DeLuca et al., 2002). Harvest losses of N

7   were estimated based on growth data from the Swedish National Forest Inventory

8   together with N concentrations in different trees (Egnell et al., 1998; Jacobson and

9   Mattson, 1998). The variation for N concentration in runoff water from growing

10   forests in Sweden is small, due to high N retention. This justifies the use of one

11   average value for southern Sweden and one value for central and northern

12   Sweden. For central and northern Sweden N leaching was calculated based on an

13   empirical relationship including runoff (Akselsson and Westling, 2005). In southern

14   Sweden N concentrations in surface water from 23 catchments were combined

15   with runoff data. The elevated concentrations after clear-cutting were included

16   according to methodologies used in earlier studies (Akselsson and Westling,

17   2005).

18

19   2.4 Monitoring data of nitrate in soil water

20   Soil water chemistry is presently measured on 64 forest sites within the Swedish

21   Throughfall Monitoring Network (Hallgren Larsson et al., 1995), along with

22   measurements of deposition of S, N and base cations. In addition there are several

23   sites where measurements have been performed until recent years. The first

1 measurements started in 1985 in the southern part of Sweden. Soil water

2 concentrations in the mineral soil at 50 cm depth have been sampled, using

3 lysimetres, three times a year, during the vegetation period as well as before and

4 after. Concentrations of e.g. sulphate, hydrogen ions, chloride, nitrate, ammonium,

5 aluminium and base cations have been analysed in the soil water.

6

7 In the present study soil water data from 88 sites were compiled, 64 of which are

8 presently running, and 24 are ended, but have been run until December 2006 or

9 later. In some cases it has not been possible to derive water, which has led to

10 missing values in the data series. In other cases the soil water amounts were very

11 small due to difficulties in deriving water, leading to large uncertainties in the

12 measured concentrations. Measurements based on sample sizes less than

13 50 mg l^{-1} (3% of the samples) were excluded from the analysis in this study due to

14 large uncertainties.

15

16 The sites were divided into seven different nitrate concentration classes based on

17 both frequency of elevated concentrations and size of the elevations (Table 1). On

18 24 of the sites only measurements before 2005 were used, since these sites were

19 affected by a storm in January 2005. In some cases there were obvious effects of

20 the storm on the nitrate leaching whereas on other sites there were only suspicions

21 about storm effects. In two cases the forest was clear-cut in 2000, and in those

22 cases only the concentrations before 2000 where included, to avoid the clear-cut

23 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

1   modeled (Belyazid et al., 2006). The focus in that study was on base cations and

2   acidification. Since then the descriptions of N cycling in the model have been

3   improved, i.e. through better differentiation between different N species and better

4   description of N reactions in anaerobic conditions. The work on refining N

5   processes in the model is still on-going. In this study, N leaching on three of the 16

6   sites has been modeled, Brattfors, Höka and Söstared, which are all pine sites.

7   The three sites are representing different N deposition regions. The modelling was

8   performed for two forest rotations, using input data from earlier studies (Belyazid et

9   al., 2006).

10

11   2.7 Weighing together the four different approaches

12   Sweden was divided into three different N status regions based on the N

13   accumulation map. Statistics on measured nitrate concentrations in soil water,

14   measured C:N ratios in the organic layer and modelled N accumulation were

15   calculated for each region. A t-test assuming equal variances was used to test if

16   there were significant differences between the regions with respect to N

17   accumulation and C:N ratios. The results were compared with the results on

18   nitrate concentrations in soil water from the dynamic modelling, where one site

19   from each region was modelled.

20

21   3 Results

22   The results from the four different approaches all showed a gradient with an

23   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).

1   [FIGURE 3]

2

3   [TABLE 3]

4

5   [FIGURE 4]

6

7   The C:N ratios varied substantially on a local scale (Fig. 5). There was, however, a

8   gradient with the highest fraction of sites with C:N below 25 in region 3 and the

9   lowest fraction in region 1 (Table 4-5). This gradient can be seen both in pine

10   forests and in spruce forests. The difference in C:N between region 1 and 3 was

11   significant both for spruce ($p<0.001$) and pine ($p<0.01$). There were strong

12   tendencies towards differences between region 2 and 3 ($p=0.06$ for spruce and

13   $p=0.08$ for pine), however not significant. The statistical analysis for region 1 and 2

14   showed no significant differences or tendencies ($p=0.28$ for spruce and $p=0.43$ for

15   pine). Within region 1 the frequency of sites with a C:N ratio below 25 was higher in

16   the southern part than in the northern part. The C:N ratios were generally higher in

17   pine forests than in spruce forests.

18

19   The NO_3 concentrations in the soil water, as modelled with ForSAFE-VEG, showed

20   increases after clear-cutting on all sites (Fig. 6). The increase was largest in

21   Söstared in region 3, and smallest in Brattfors in region 1. In Brattfors and Höka

22   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.

1

2   In region 2, i.e. the southern part of Sweden except the most southwestern part,

3   the N accumulation in the forest ecosystems was higher, and there was a gradient

4   with higher accumulation to the southwest. The frequency of C:N ratios below 25

5   was about the same as in the southern part of region 1. In the southwestern part of

6   region 2 there were a few sites with elevated nitrate concentrations in soil water.

7   The dynamic modelling in Höka showed a similar pattern as for Brattfors in the

8   northern region 1, but the nitrate concentration after clear-cutting was higher and

9   the elevated nitrate concentrations persisted for a longer time. Hence, region 2

10 was assessed as a risk area for elevated N leaching, although the risk was

11 relatively small. The risk was deemed to be highest in the southwestern part of

12 region 2.

13

14 In region 3, i.e the southwestern part of Sweden, the N accumulation in the forest

15 ecosystems was generally above 8 kg ha^{-1} y^{-1} and the C:N ratios in the organic soil

16 layer were lower than in the rest of Sweden. The nitrate concentrations in soil

17 water were elevated on several of the sites. The dynamic modelling in Söstared

18 showed substantially elevated soil water nitrate concentrations after clear-cutting,

19 and the elevation persisted during the whole forest rotation, in contrast to the

20 results in Höka and Brattfors. Region 3 was, based on these results, assessed as

21 an area with considerable risk of elevated N leaching.

22

1   Although there were clear differences between the three regions, the variation

2   within a region was also large, which was evident for the C:N ratios and the nitrate

3   concentrations. The risk assessments above refer to the general conditions for a

4   specific region, but on a local scale the risk can differ substantially from the

5   average risk of the region to which it belongs. Thus site characteristics are

6   important in estimating the risk of nitrate leaching on a local scale.

7

8   The risk analysis can be used as a basis for policy making, e.g in abatement

9   strategies of N emission reductions, and in advising the forest sector about N

10 fertilization, harvesting of forest fuels and methods for clear cuttings. However, the

11 risk analysis is based merely on the risk of N leaching. In region 1, which was

12 assessed as a low risk area, the main risk of damage from N deposition is change

13 in ground vegetation distribution (Nordin et al., 2005). Furthermore, the risk

14 analysis presented in this study was based on current conditions. A future

15 intensified forest management practice, with increased N fertilization in a changing

16 climate, may affect the risk of leaching.

17

18 All approaches are associated with strengths and weaknesses. Using a single one

19 of the four different approaches would lead to large uncertainties, but by combining

20 the four approaches, as was done in this study, the strengths of the different

21 approaches are combined, and the uncertainties in the final assessments become

22 smaller. The strength with the monitoring data is that it is real data, which shows

23 the actual status in the forest. The strength with the modelled data is that it is

1   possible to scale up, both spatially, with the mass balance model, and temporally,

2   with the dynamic model.

3

4   Measuring nitrate concentrations in the soil water is the only method where nitrate

5   leaching, or at least the first step of nitrate leaching, is actually measured. Thus

6   this is a very important dataset and these measurements should be continued in

7   order to keep track of changes in the soil water quality. The C:N ratios in the

8   organic soil layer should be seen only as a first rough method to estimate the risk

9   of leaching. The method is applicable mainly on an European level, to distinguish

10 between high risk areas (with low C:N ratios) and low risk areas (with high C:N

11 ratios) (Gundersen, 1998). However, as pointed out in Gundersen (1998), there is

12 a large variation in the span 25-30, which applies for southern Sweden, with soil

13 water nitrogen concentrations ranging between 0 and 20 mg l^{-1}. This indicates that

14 there are other important factors that are determinant for nitrate leaching. Recent

15 reviews have suggested differences in microbial activity as a possible explanation

16 for the difference in nitrate leaching between sites (Booth et al., 2005; Emmett,

17 2007). Furthermore, future climate change may greatly affect N processes in soils

18 due to effects on e.g. soil hydrology, soil organisms and plant growth, confounding

19 the presumed relationship between C:N ratio and N leaching.

20

21 With the mass balance calculations, the forest ecosystem N status gradient is

22 captured, and scenario calculations can be done for e.g. different deposition and

23 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.

1 The monitoring and modelling approaches are associated with different strengths

2 and weaknesses. Basing the assessment on four different approaches, as was

3 done in this study, makes it more robust than if only one single approach was

4 used. Furthermore, the different approaches have different resolution in time and

5 space, and through the combination of the methods the best possible resolution in

6 both time and space can be obtained. There are still knowledge gaps about N

7 cycling and how it is affected by climate change. Experimental approaches and

8 environmental monitoring data are important to improve the knowledge. Dynamic

9 modelling in well investigated sites is an appropriate way for increased process

10 understanding and improved modelling of the N cycling.

11

16

17 References

18 Aber, J.D., Nadelhoffer, K.J., Steudler, P., Melillo, J.M., 1989. Nitrogen saturation

19 in northern forest ecosystems. Bioscience 12, 378-186.

20 Akselsson C., Westling O., 2005. Regionalized nitrogen budgets in forest soils for

21 different deposition and forestry scenarios in Sweden. Global Ecology and

22 Biogeography 14, 85–95.

1 Akselsson C., Westling O., Örlander G., 2004. Regional mapping of nitrogen

2 leaching from clearcuts in southern Sweden. Forest Ecology and Management

3 202, 235-243.

4 Akselsson, C., Westling, O., Alveteg, M., Thelin, G., Fransson, A-M., Hellsten, S.,

5 2008. The influence of N load and harvest intensity on the risk of P limitation in

6 Swedish forest soils. Science of the Total Environment 404, 284-289.

7 Belyazid, S., Westling, O., Sverdrup, H., 2006. Modelling changes in forest soil

8 chemistry at 16 Swedish coniferous forest sites following deposition reduction.

9 Environmental Pollution 144, 596-609.

10 Belyazid, S., Kurz, D., Sverdrup, H., Braun, S., Rhim, B., 2009. Developing a

11 method for estimating critical loads of nitrogen deposition under a changing

12 climate, based on biological indicators, in: Hettelingh, J-P., Posch, M., Slootweg, J.

13 (Eds.), Progress in the modelling of critical thresholds, impacts to plant species

14 diversity and ecosystem services in Europe, CCE Status Report 2009, pp. 55-67.

15 Booth, M.S., Stark, J.M., Rastetter, E., 2005. Controls on nitrogen cycling in

16 terrestrial ecosystems: A synthetic analysis of literature data. Ecological

17 Monographs 75, 139-157.

18 Cowling, E., Galloway, J., Furiness, C., Barber, M., Bresser, T., Cassman, K.,

19 Erisman, J., Haeuber, R., Howarth, R., Melillo, J., Moomaw, W., Mosier, A.,

20 Sanders, K., Seitzinger, S., Smeulders, S., Socolow, R., Walters, D., West, F.,

21 Zhu, Z., 2001. Optimizing Nitrogen Management in Food and Energy Production

22 and Environmental Protection: Summary Statement from the Second International

1   Nitrogen Conference, in: Galloway, J., Cowling, E., Erisman, J.W., Wisniewski, J.,

2   Jordan, C. (Eds.), Contributing papers from the 2nd international nitrogen

3   conference 14-18 October 2001, Potomac, Maryland, USA: Optimizing Nitrogen

4   Management in Food and Energy Production and Environmental Protection, pp. 1-

5   9.

6   DeLuca, H., Zackrisson, O., Nilsson, M.C., Sellstedt, A., 2002. Quantifying

7   nitrogen-fixation in feather moss carpets of boreal forests. Nature 419, 917–20.

8   Egnell, G., Nohrstedt, H-Ö., Weslien, J., Westling, O., Örlander, G., 1998.

9   Miljökonsekvensbeskrivning av skogsbränsleuttag, asktillförsel och övrig

10   näringskompensation. Swedish Forest Agency Report 1:1998, Jönköping, Sweden.

11   (In Swedish).

12   Emmett, B., 2007. Nitrogen saturation of terrestrial ecosystems: Some recent

13   findings and their implications for our conceptual framework. Water, Air and Soil

14   Pollution: Focus 7, 99-109.

15   Gundersen, P., Callesen, I., de Vries, W., 1998. Nitrate leaching in forest

16   ecosystems is related to forest floor C/N ratios. Environmental Pollution 102, 403-

17   407.

18   Gundersen, P., Schmidt, I., Rauland-Rasmussen, K., 2006. Leaching of nitrate

19   from temperate forests – effects of air pollution and forest management.

20   Environmental Reviews 14, 1-57.

21   Hägglund, B., 1985. En ny svensk riksskogstaxering (A new Swedish National

22   Forest Survey). Swedish University of Agricultural Sciences Report 37, Swedish

1 University of Agricultural Sciences, Uppsala, Sweden. (In Swedish with English

2 summary).

3 Hallgren Larsson, E., Knulst, J., Malm, G., Westling, O., 1995. Deposition of

4 acidifying compounds in Sweden. Water, Air and Soil Pollution 85, 2271-2276.

5 Hånell, B., 1990. Torvtäckta marker, dikning och sumpskogar i Sverige.

6 Skogsfakta, 22, Uppsala, Sweden. (In Swedish).

7 Hermann M., Sharpe, W.E., DeWalle, D.R., Swistock, B.R., 2001. Nitrogen export

8 from watershed subjected to partial salvage logging, in: Galloway, J., Cowling, E.,

9 Erisman, J.W., Wisniewski, J., Jordan, C. (Eds.), Contributing papers from the 2nd

10 international nitrogen conference 14-18 October 2001, Potomac, Maryland, USA:

11 Optimizing Nitrogen Management in Food and Energy Production and

12 Environmental Protection, pp. 440-448.

13 Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P, Xiaosu, D.

14 (Eds.), 2001. Climate Change 2001: The Scientific Basis. IPCC, Cambridge Univ.

15 Press, contribution of Working Group I to the Third Assessment Report of the

16 Intergovernmental Panel on Climate Change (IPCC).

17 Jacobson, S., Mattson, S., 1998. "Snurran"—an Excel program for calculating site

18 nutrient levels in logging residues. The Forestry Research Institute of Sweden

19 Report, 1. (In Swedish with English summary).

20 Langner, J., Persson, C., Robertson, L., Ullerstig, A., 1996. Air pollution

21 assessment study using the MATCH Modelling System. Application to sulphur and

1   nitrogen compounds over Sweden 1994. Swedish Meteorological and Hydrological

2   Institute Report, 69, Norrköping, Sweden.

3   Lundin, L., 1999. Effects on hydrology and surface water chemistry of regeneration

4   cuttings in peatland forests. International peat journal 9, 118-126.

5   Lundin, L., Bergquist, B., 1990. Effects on water chemistry after drainage of a bog

6   for forestry. Hydrobiologia 196, 167-181.

7   Nordin, A., Strengbom, J., Witzell, J., Näsholm, T., Ericson, L., 2005. Nitrogen

8   deposition and the biodiversity of boreal forests – implications for the nitrogen

9   critical load. Ambio 34, 20-24.

10   Pardo L.H., Driscoll C.T., Likens G.E., 1995. Patterns of nitrate loss from a

11   chronosequence of clear-cut watersheds. Water, Air and Soil Pollution 85, 1659-

12   1664.

13   Raab, B., Vedin, H. (Eds.), 1995. Klimat, sjöar och vattendrag. SNA Förlag,

14   Stockholm, Sweden. (In Swedish).

15   Stokland, J.N., Eriksen, R., Tomter, S.M., Korhonen, K., Tomppo, E., Rajaniemi,

16   S., Söderberg, U., Toet, H., Riis-Nielsen, T. (2003) Forest biodiversity indicators in

17   the Nordic countries. TemaNord 2003:514, Copenhagen, Denmark.

18   Swedish Forest Agency, 2000. Skogliga konsekvensanalyser 1999. Swedish

19   Forest Agency Report, 2:2000, Jönköping, Sweden. (In Swedish).

20   Swedish Forest Agency, 2008. Statistical Yearbook of Forestry 2008. Swedish

21   Forest Agency, Jönköping, Sweden. (In Swedish with some features in English).

1 Swedish University of Agricultural Sciences, 2008. Skogsdata 2008. Department of

2 Forest Resource Management, Swedish University of Agricultural Sciences. (In

3 Swedish with some features in English).

4 Tamm, C.O., 1991. Nitrogen in terrestrial ecosystems. Ecological Studies 81.

5 Springer Verlag, Berlin, Germany.

6 van Breemen, N., Jenkins, A., Wright, R., Beerling, D., Arp, W., Berendse, F. Beier,

7 C., Collins, R., van Dam, D., Rasmussen, L., Verburg, P., Wills, M., 1998. Impacts

8 of Elevated Carbon Dioxide and Temperature on a Boreal Forest Ecosystem

9 (CLIMEX Project). Ecosystems 1, 345–351.

10 Wallman, P., Svensson, M., Sverdrup, H., Belyazid, S., 2005. ForSAFE - an

11 integrated process-oriented forest model for long-term sustainability assessments.

12 Forest Ecology and Management 207, 19-36.

13

1 Tables

2 Table 1. Criteria for division into nitrate concentration classes.

3

4 Class	Description	Criteria
5 1	Very low concentrations	Max. conc. <0.01 mg l^{-1}
6 2		Max. conc. betw. 0.01 & 0.1 mg l^{-1}
7 3		One conc. >0.1 but <0.5 mg l^{-1}
8 4		Several conc. >0.1 but < 0.5 mg l^{-1}
9 5		One conc. > 0.5 mg l^{-1}
10 6		At least two conc. > 0.5 mg l^{-1}
11 7	Substantially elevated concentrations	Mean conc. >1 mg l^{-1}

12

13

14 Table 2. Statistics for the N accumulation (kg ha^{-1} y^{-1}) estimated from the nitrogen

15 balance modelling in the three areas, for spruce and pine separately.

16

17	Spruce			Pine		
18 Region	Median	95-perc.	5-perc.	Median	95-perc.	5-perc.
19 1	2.5	4.0	1.2	2.6	5.3	1.1
20 2	6.2	7.8	4.4	7.2	9.5	5.5
21 3	8.5	10.0	6.7	11.1	13.1	9.0

22

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

2   Table 1).

3

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

7

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

9   spruce.

10

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

15

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

17

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

22

1   Figures

2

N deposition (mg m^{-2})
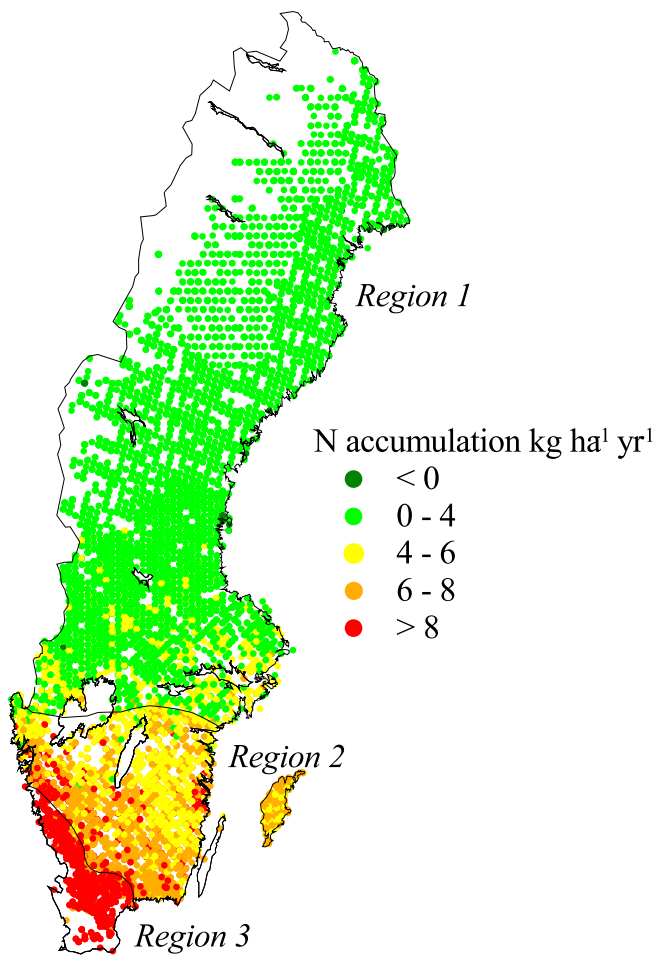< 500
500 - 1000
1000 - 1500
1500 - 2000
2000 - 2500
> 2500
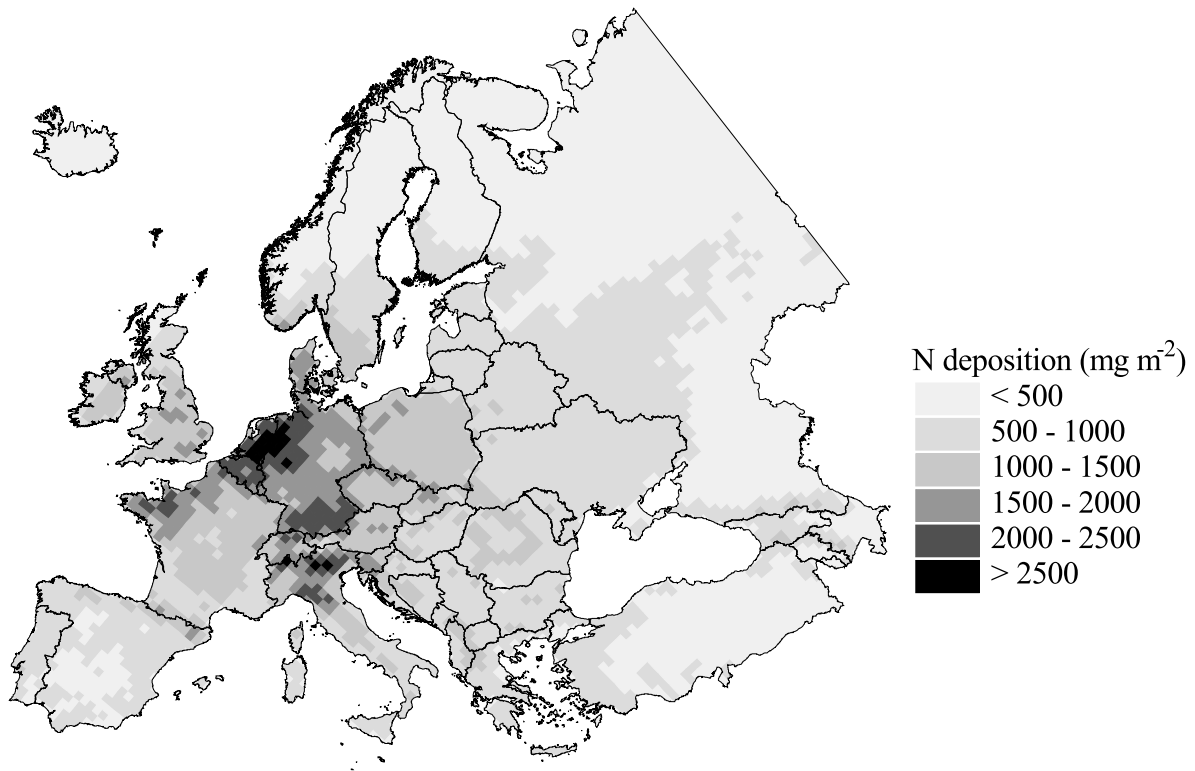
3

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

5   EMEP model.

6

N accumulation kg ha^1 yr^1

- < 0
- 0 - 4
- 4 - 6
- 6 - 8
- > 8

Region 1

Region 2

Region 3

1

2 Fig. 2. N accumulation estimated from the nitrogen balance modelling in 5641

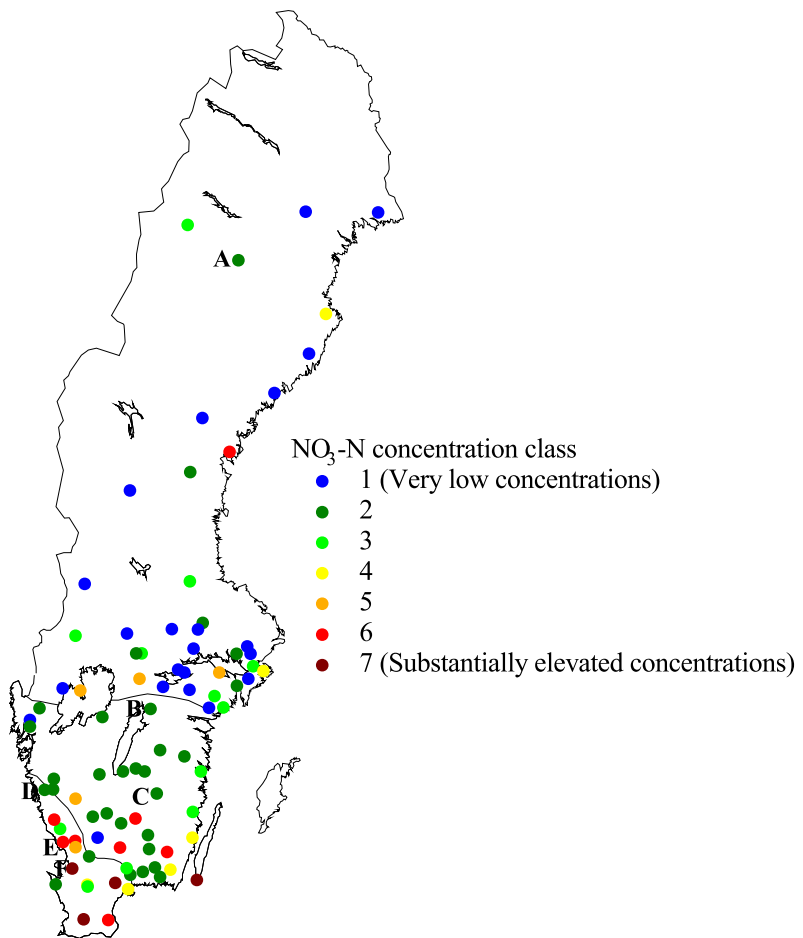3 spruce sites and 6749 pine sites in Sweden. Based on the N accumulation,
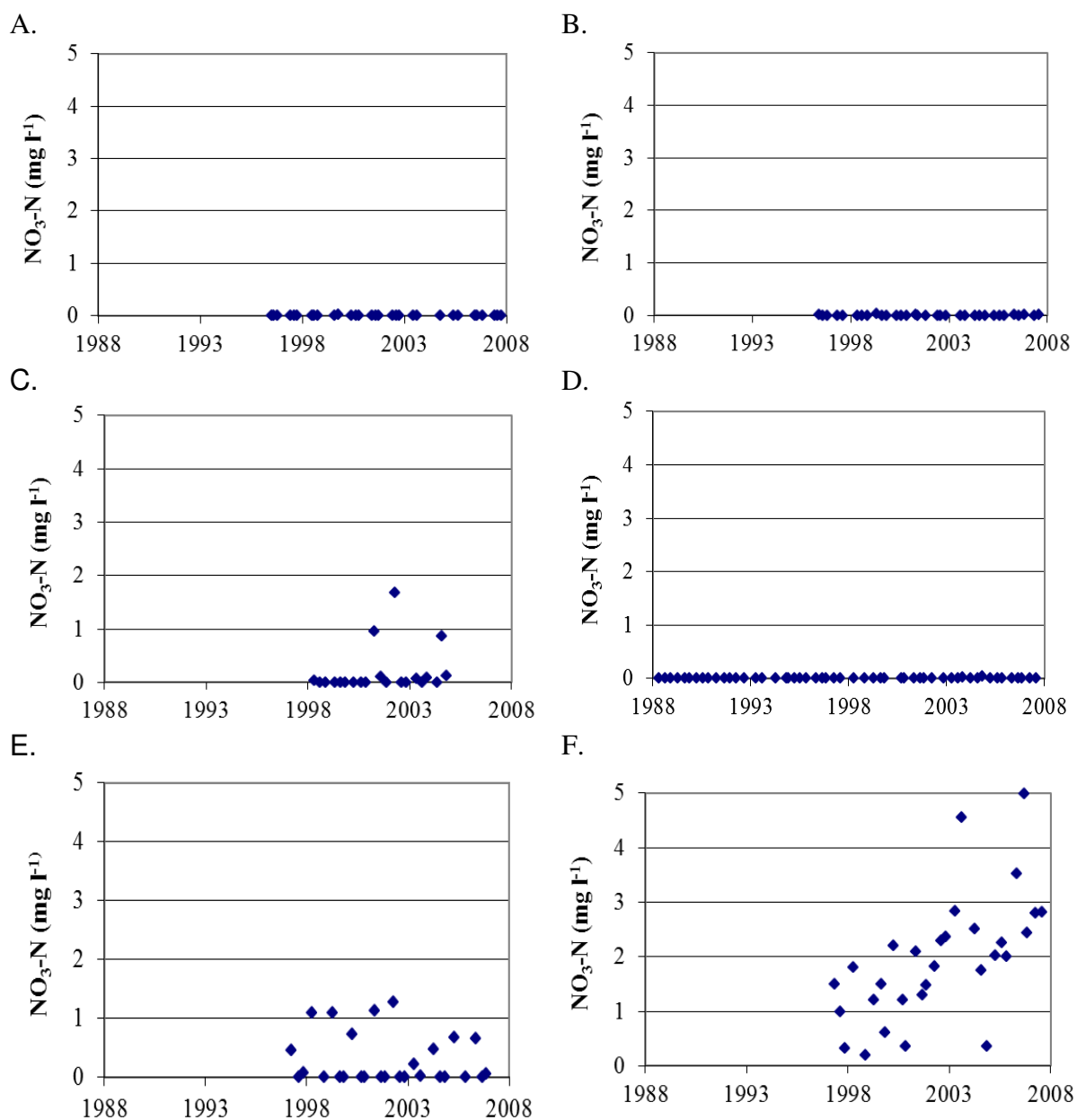
4 Sweden was divided in three regions.

5

1

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.

5

6

1

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.
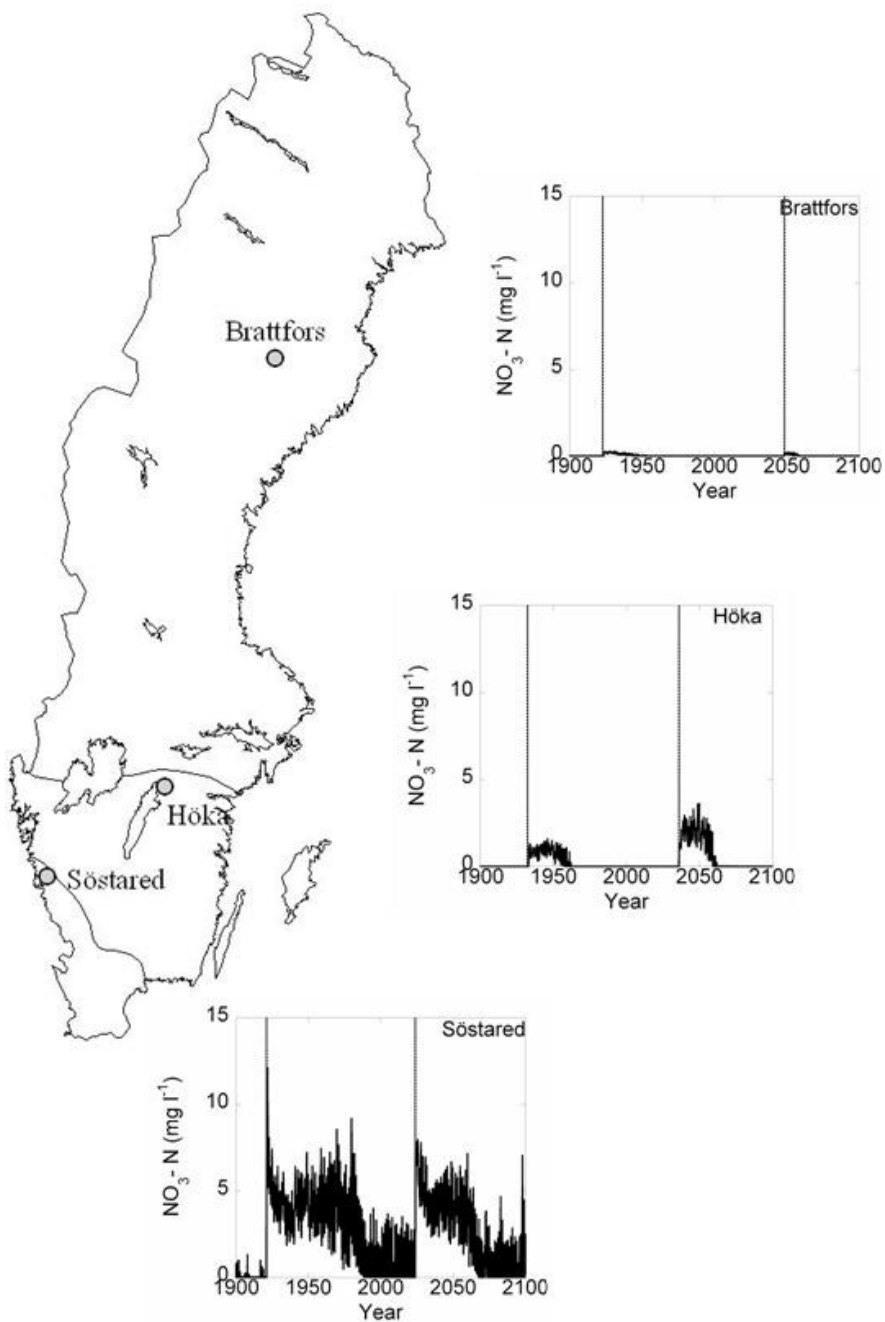
8
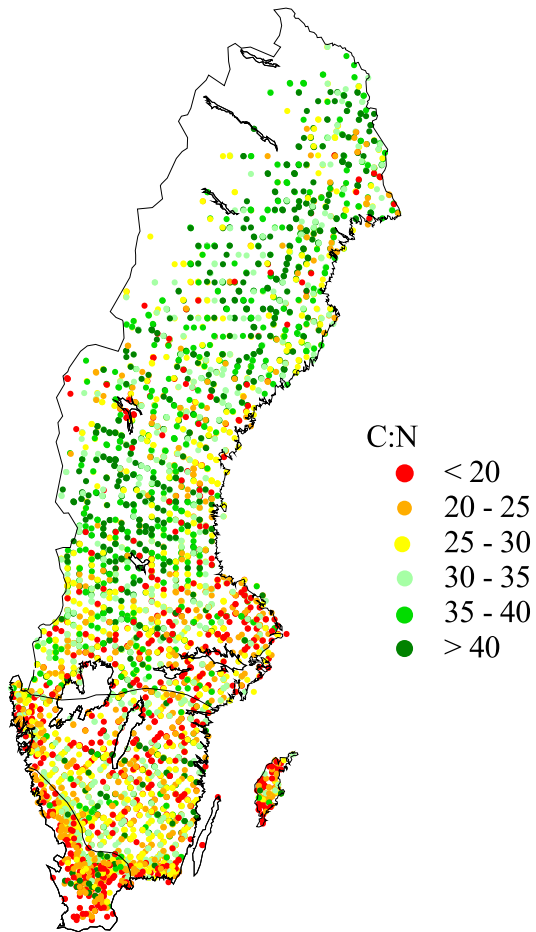
1

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

3

1

2 Fig. 6. Concentration of nitrate (NO$_3$-N) in soil water (μekv l^{-1}) in pine forests in

3 Brattfors, Höka and Söstared 1900-2100 as modeled with the ForSAFE-VEG

4 model. Vertical lines are clearcuts.