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

Akselsson, Cecilia; Belyazid, Salim; Hellsten, Sofie; Klarqvist, Malin; Pihl-Karlsson, Gunilla; Karlsson, Per-Erik; Lundin, Lars

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PO Box 117
221 00 Lund
+46 46-222 00 00

1 Title

2 Assessing the risk of N leaching from forest soils across a steep N deposition

3 gradient in Sweden

4

5 Authors and affiliations

6 Cecilia Akselsson^a (corresponding author), Salim Belyazid^b, Sofie Hellsten^c, Malin

7 Klarqvist^{c 1}, Gunilla Pihl-Karlsson^c, Per-Erik Karlsson^c, Lars Lundin^d

8

9 ^aDepartment of Earth and Ecosystem Sciences, Lund University, Sölvegatan 12,

10 SE-223 62 Lund, Sweden, Phone: +46 46-222 86 89, Fax: +46 46-222 03 21,

11 E-mail: cecilia.akselsson@nateko.lu.se

12

13 ^bBelyazid Consulting and Communication, Stationsvägen 13, SE-517 34

14 Bollebygd, Sweden, salim@belyazid.com

15

16 ^cIVL Swedish Environmental Research Institute, Box 5302, SE-400 14 Gothenburg,

17 Sweden, sofie.hellsten@ivl.se, gunilla@ivl.se, per-erik.karlsson@ivl.se

18

19 ^dSwedish University of Agricultural Sciences, Box 7001, 750 07 Uppsala,

20 lars.lundin@mark.slu.se

21

22 ¹Present address: Stadsbyggnadskontoret, City of Gothenburg, P.O Box 2554, SE-

23 403 17 Gothenburg

1 Abstract

2 Nitrogen leaching from boreal and temperal 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 55°N and 69°N, and therefore the climate
15 varies considerably throughout the country. The transition from temperate to boreal
16 climate is at around 60°N. 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 0°C in the south and -16°C in the north. The
20 corresponding values for the summer are 16 and 8°C (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 ($\text{NO}_3\text{-N}$) 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

1 changes whereas net losses mean strengthened N limitation and a risk of negative
2 effects on tree growth. Mass balance calculations capture the gradient of the N
3 status, whereas it is difficult to relate the accumulation rates to an actual risk of N
4 leaching.

5

6 Nitrate concentrations in soil water in northern forest ecosystems are generally low,
7 since the forests are N limited and take up all available N. Elevated nitrate
8 concentrations indicate an excess of N. The Swedish Throughfall Monitoring
9 Network has long time series of element concentrations, e.g. nitrate, in soil water at
10 50 cm depth in the mineral soil, on many sites covering the whole country. These
11 time series can be used for identifying areas where nitrate concentrations are
12 elevated, indicating a risk of large-scale N leaching.

13

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

20

21 The dynamic model ForSAFE-VEG (Wallman et al., 2005; Belyazid et al., 2006)
22 includes process-based descriptions of weathering, soil chemistry, decomposition,
23 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

$$14 \quad \Delta = \text{Deposition} + \text{Fixation} - \text{Harvesting} - \text{Leaching}$$

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 were included, to avoid the clear-cut
23 effect. The storm- and clear-cut effects will be evaluated in separate studies, and

1 were not included here since this study refers to undisturbed growing forests. On
2 most of the sites the measurements started in the end of the 1980's or in the
3 1990's. On four sites the measurements started after year 2000.

4

5 [TABLE 1]

6

7 2.5 Monitoring data of C:N in the organic layer

8 Within the Swedish National Forest Soil Inventory (Hägglund, 1985), managed by
9 the Swedish University of Agricultural Sciences in Uppsala, C and N
10 concentrations in the soil organic layer have been measured on 5537 sites
11 between 1993 and 1998. In this study, the C:N ratios for these sites were used.
12 Ratios below 25 indicate an increased risk of N leaching, based on empirical
13 studies (Gundersen et al., 1998) and thus the frequency of sites with ratios below
14 25 in different regions were estimated. Furthermore the variation in ratios was
15 related to tree species.

16

17

18 2.6 Modelled N dynamics with the dynamic model ForSAFE-VEG

19 The ForSAFE-VEG model (Wallman et al., 2005; Belyazid et al., 2006) is a
20 dynamic and mechanistic ecosystem model, handling weathering, soil chemistry,
21 decomposition, tree growth, ground vegetation and hydrology. The model can be
22 used for simulating effects of climate change, forestry and changed deposition on
23 acidification, N cycling, tree growth and ground vegetation. A first attempt to use
24 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

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

12

13 [FIGURE 2]

14

15 [TABLE 2]

16

17 Nitrate concentrations in the soil water were very low on many sites (Fig. 3, Table
18 3). Sites with very low concentrations were abundant in all regions (Fig. 3; Fig.
19 4(a), 4(b) and 4(d)). Most of the sites with elevated concentrations, temporarily or
20 chronically, were situated in region 3 (Fig. 3; Figs 4(e) and 4(f); Table 3). There
21 were, however a number of sites with elevated concentrations also in region 2 (Fig.
22 3; Fig. 4(c); Table 3).

23

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

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

3 [FIGURE 5]

4

5 [TABLE 4]

6

7 [TABLE 5]

8

9 [FIGURE 6]

10

11 4 Discussion

12 The results from the four different approaches all showed a gradient with higher N
13 status in the southern part of Sweden than in the north. In region 1, corresponding
14 to the northern and central part of Sweden, the risk of elevated N leaching was
15 estimated to be small. The accumulation of N was low, the nitrate concentration in
16 soil water was generally very low and the C:N ratios were generally above 25. The
17 dynamic modelling in Brattfors showed small increases in soil water nitrate
18 concentrations after clear-cutting, but the concentrations then returned to normal,
19 very low levels. In the southern part of region 1 the frequency of sites with C:N
20 ratios < 25 was somewhat higher than in the northern part, and the N accumulation
21 was somewhat higher, but there were no signs of elevated concentrations in the
22 soil water, and thus the overall conclusion about a low risk of elevated N leaching
23 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 $8 \text{ kg ha}^{-1} \text{ y}^{-1}$ 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

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

10

11 Combining modelling and experimental approaches is important for increased
12 process understanding. By running dynamic models in well investigated sites, such
13 as experimental or environmental monitoring sites, the process understanding can
14 be increased and the dynamic models can be continuously improved. Two of the
15 sites modelled with ForSAFE-VEG are included in the 88 Swedish Throughfall
16 Monitoring Network sites investigated in this study, Höka and Söstared. Höka, the
17 site in region 2, shows very low soil water nitrate concentration in the
18 measurements, which is similar to the model results. The modelled soil water
19 nitrate concentrations are elevated for some time after clear-cutting, but then
20 returns to low levels. The soil water nitrate concentrations in the measurements in
21 Söstared are also very low. However, the model results show elevated soil water
22 nitrate concentrations after a simulated clear cutting during the whole subsequent
23 rotation period, with a peak just after clear-cutting. In-depth analysis of the

1 difference between the modelled and measured soil water nitrate concentrations in
2 Söstared can be one of the keys to increased understanding of soil N retention
3 processes. The concentrations after clear-cutting according to the modelling are
4 reasonable, as compared with measured concentrations. In the modelled clear-cut
5 in the 21st century, the maximum soil water nitrate concentration was 0.2 mg l⁻¹ in
6 the northern site, 3.6 mg l⁻¹ in the middle site and 8.0 mg l⁻¹ in the southwestern
7 site. Measurements on 24 sites in southern Sweden showed concentrations after
8 clear-cutting between 0.2 and 5.7 mg l⁻¹ (Akselsson et al., 2004), i.e. the same
9 magnitude as the modelled concentrations. The duration of the leaching event after
10 clear-cutting was, however, overestimated by the model on all three sites due to
11 the fact that uptake by understorey vegetation is not included in the model at this
12 stage.

13

14 Future climate scenarios show large changes in temperature and precipitation in
15 the near future (Houghton et al., 2001). This will change the conditions in forest
16 soils, through the impact on important ecosystem processes such as
17 decomposition, weathering, percolation and tree growth. Furthermore, forestry will
18 most likely be intensified to meet the increasing demand of biofuels. N fertilization
19 may become more widespread. Of the different methods applied in this study, the
20 dynamic modelling approach with ForSAFE-VEG is the only one that can be used
21 for assessing effects of climate change. The climate scenario adopted gradually
22 diverges from the control scenario of no climate change, starting from 2010. The
23 effects of climate change on N leaching are therefore discussed for the second

1 clear-cut events shown in Fig. 6. At the three sites, clear-cutting events trigger a
2 peak in NO₃ leaching. The duration and magnitude of leaching is affected by the
3 climatic conditions, as well as by the atmospheric deposition, the harvest intensity
4 and the site conditions. At the northern site Brattfors, a change in climate will result
5 in a lower leaching magnitude with a shorter duration following clear-cutting. Higher
6 temperatures in the future will contribute more to increasing forest growth rates,
7 and subsequently nitrogen uptake by the roots, than to the release of N through
8 decomposition and mineralization. At the central site, Höka, the opposite will occur.
9 The future change in climate will release large amounts of accumulated N in the
10 soil, and the marginal increase in forest growth rates due to higher temperatures
11 will not suffice for the roots to take up all the released N. Finally, at the southern
12 site Söstared, climate change will lead to higher N leaching in the short term
13 following the clear-cut, but to lower N leaching later on in the rotation period,
14 according to the model results.

15

16 5 Conclusions

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

22

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

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14 Swedish Environmental Protection Agency, through the SCARP programme
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16

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- 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
4 1	0	3	3
5 2	3	12	15
6 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

11 Region	Median	95-perc.	5-perc.	Percentage with C:N<25 (%)
12 1	29	43	16	29
13 2	26	34	17	42
14 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.

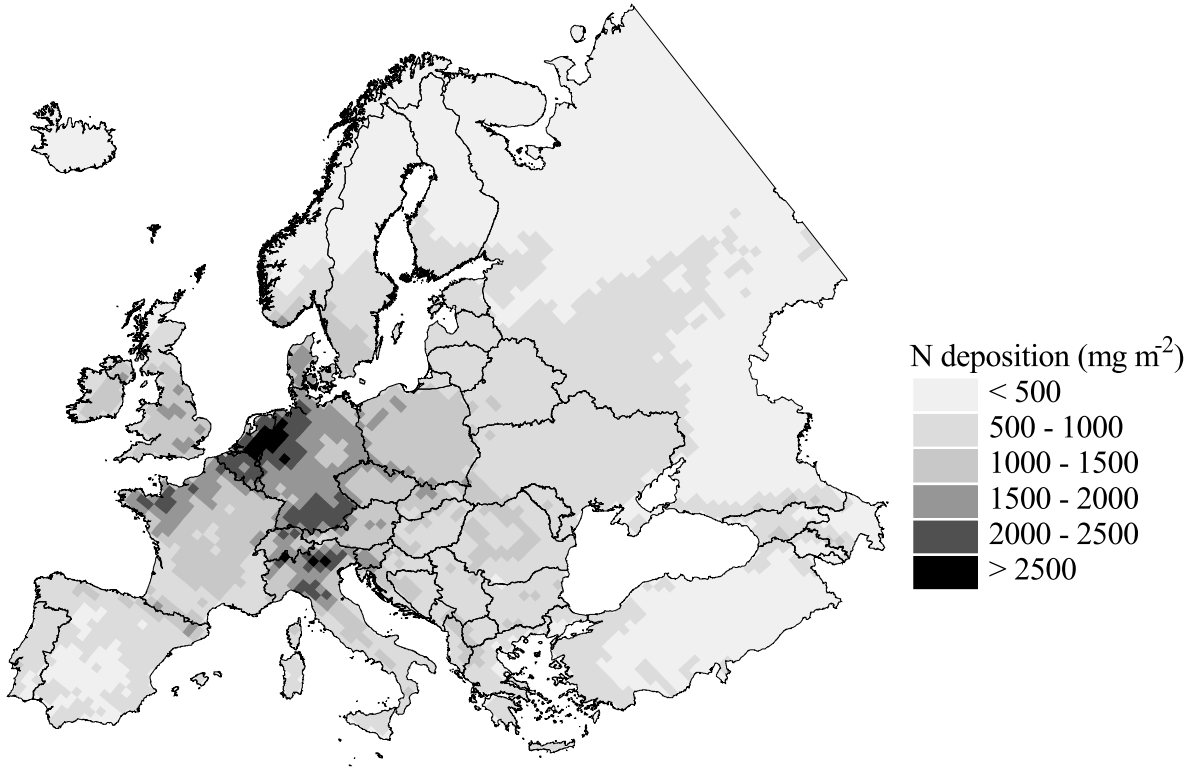
17

18 Region	Median	95-perc.	5-perc.	Percentage with C:N<25 (%)
19 1	36	55	21	12
20 2	32	45	21	16
21 3	28	40	18	36

22

1 Figures

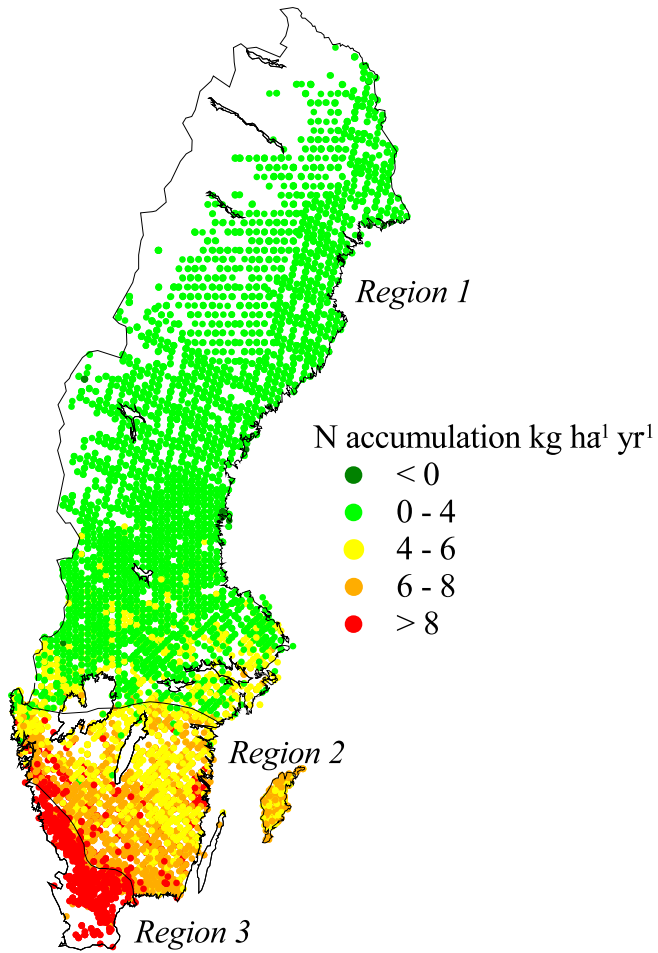
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3

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

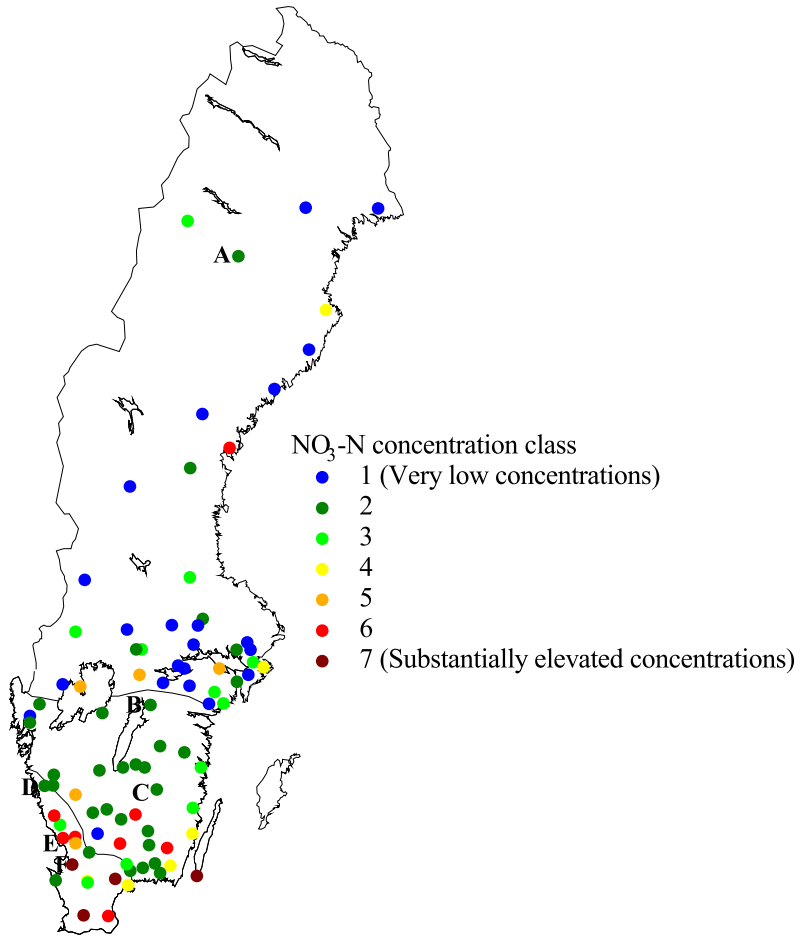
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1

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



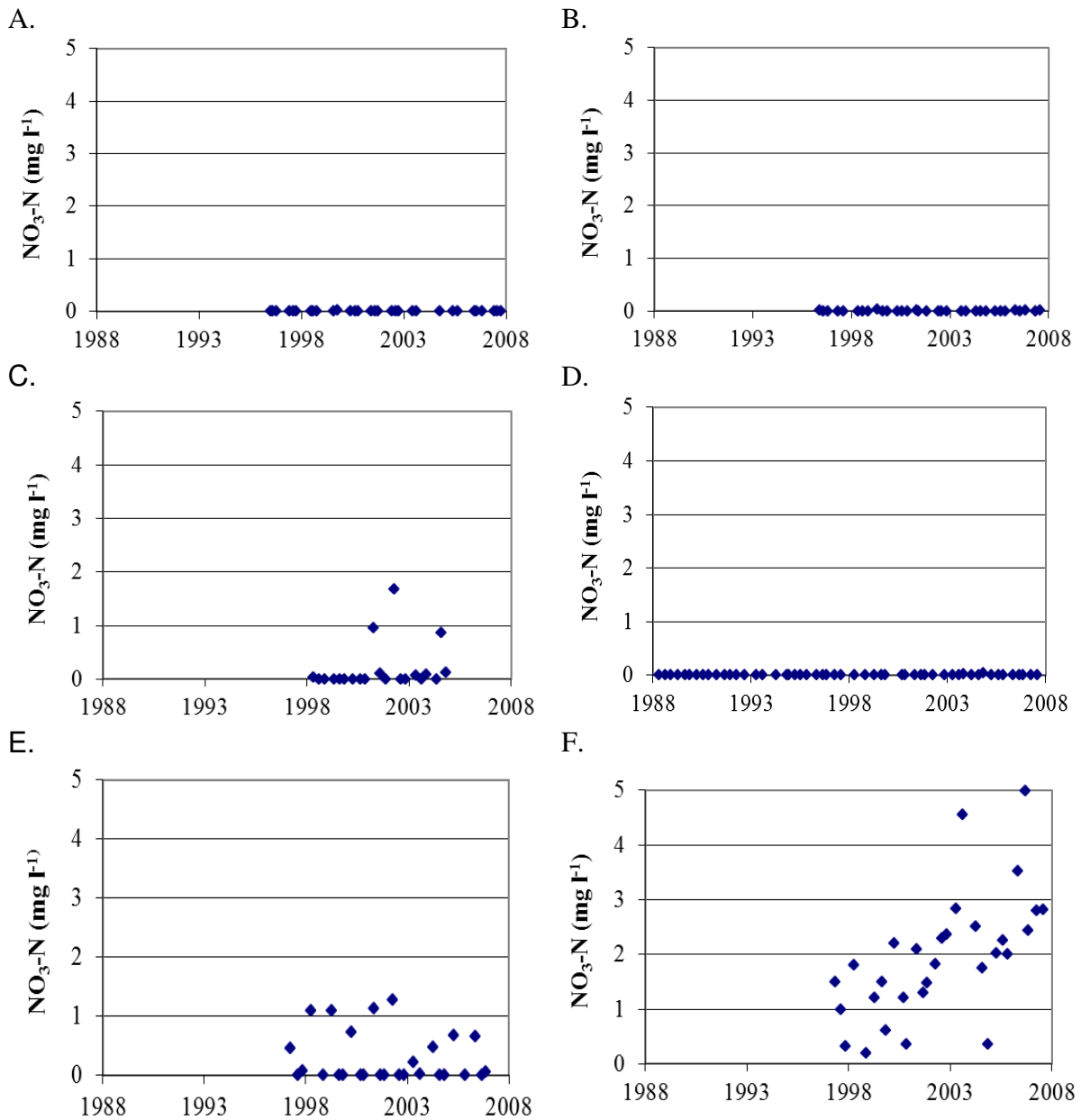
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2 Fig. 3. 88 sites in the Swedish Throughfall Monitoring Network divided into seven
 3 classes with different nitrate (NO₃-N) concentration according to Table 1. Graphs
 4 for the sites A-F are shown in Figure 4.

5

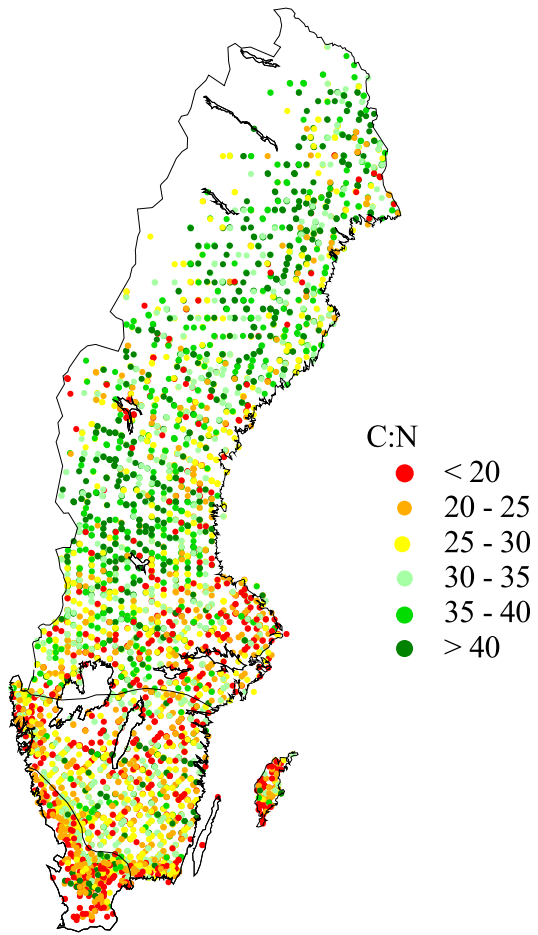
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2 Fig. 4. Nitrate ($\text{NO}_3\text{-N}$) concentrations in soil water in Högbränna, Norway spruce,
3 92 years (a), Höka, Scots pine, 72 years (b), Asa, Norway spruce, 46 years (c),
4 Söstared, Scots pine, 84 years (d), Fastarp, Norway spruce, 71 years (e) and
5 Vallåsen, Norway spruce, 70 years (f). The location of the sites is shown in Figure
6 3. The age of the trees refers to 2007, the year from which the last data in this
7 study derives.

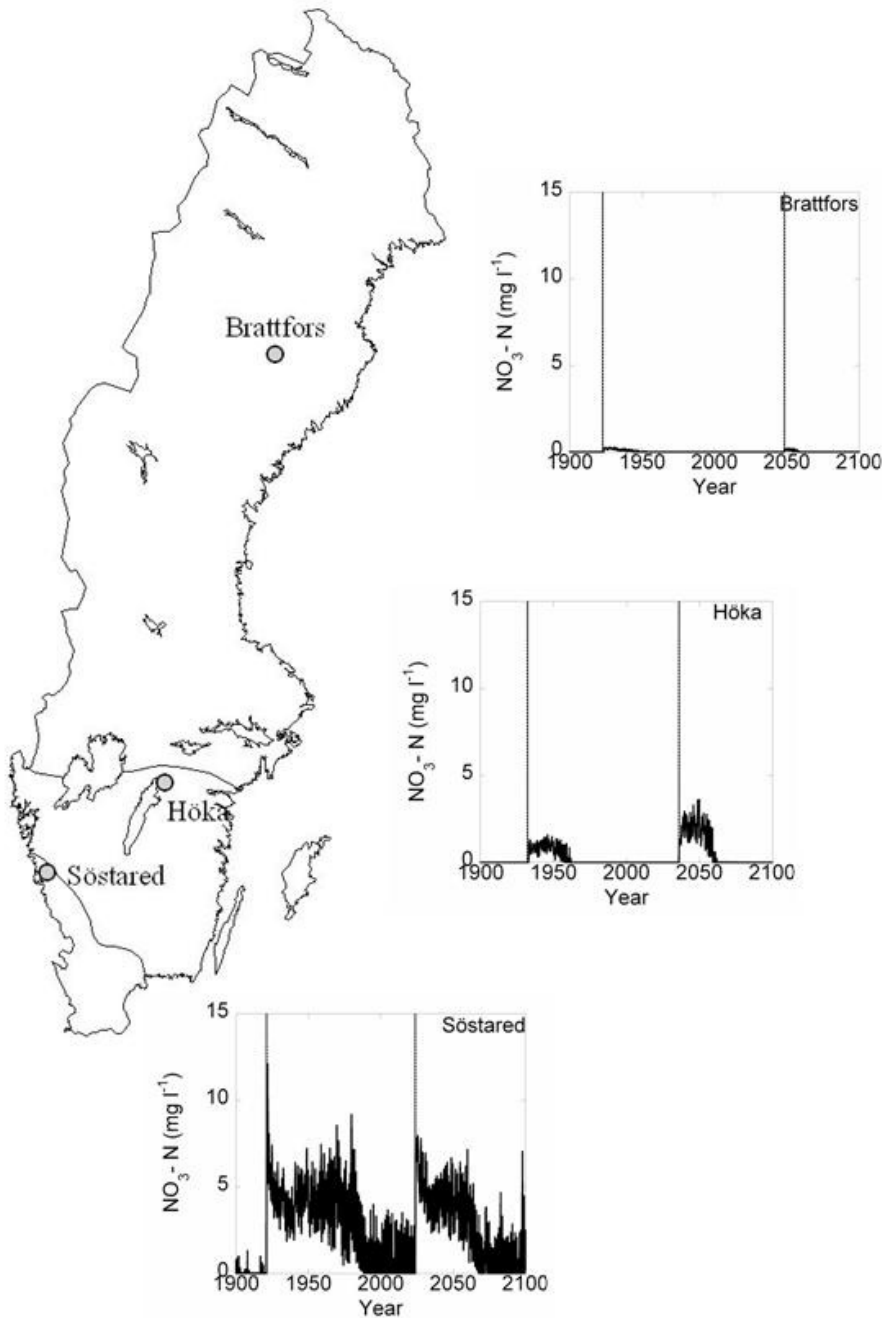
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1

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

3



1

2 Fig. 6. Concentration of nitrate ($\text{NO}_3\text{-N}$) in soil water ($\mu\text{ekv l}^{-1}$) in pine forests in
 3 Brattfors, Höka and Söstared 1900-2100 as modeled with the ForSAFE-VEG
 4 model. Vertical lines are clearcuts.