

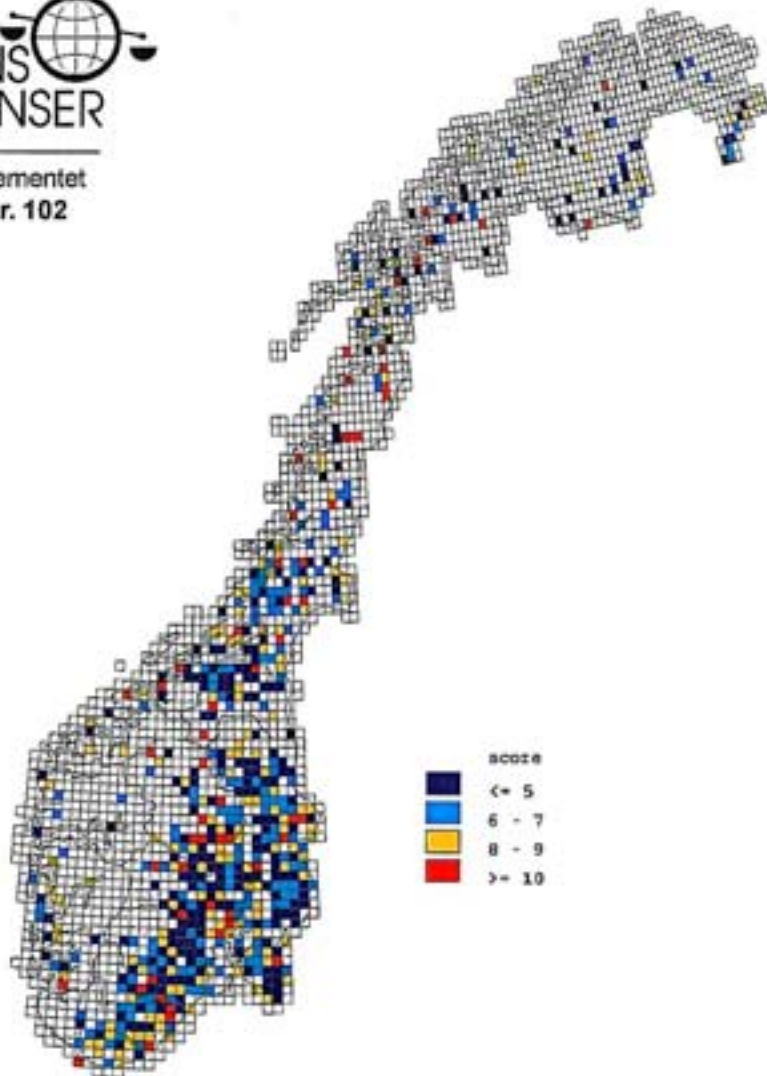


REPORT SNO 4038-99

Risk of N leaching from forests to waters in Norway

NATURENS
TALEGRENSER

Miljøverndepartementet
Fagrappport nr. 102



Naturens Tålegrenser

Programmet Naturens Tålegrenser ble satt igang i 1989 i regi av Miljøverndepartementet. Programmet skal blant annet gi innspill til arbeidet med Nordisk Handlingsplan mot Luftforurensninger og til pågående aktiviteter under Konvensjonen for Langtransporterte Grensoverskridende Luftforurensninger (Genevekonvensjonen). I arbeidet under Genevekonvensjonen er det vedtatt at kritiske belastningsgrenser skal legges til grunn ved utarbeidelse av nye avtaler om utslippsbegrensning av svovel, nitrogen og hydrokarboner.

En styringsgruppe i Miljøverndepartementet har det overordnede ansvar for programmet, mens ansvaret for den faglige oppfølgingen er overlatt en arbeidsgruppe bestående av representanter fra Direktoratet for naturforvaltning (DN), Norsk polarinstitutt (NP) og Statens forurensningstilsyn (SFT).

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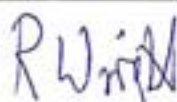
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Abstract

Data from soil surveys, lake surveys and deposition measurements for 634 squares of a 12x12 km grid in forest areas of Norway show that leaching of NO_3 from forested areas of Norway is strongly related to N deposition but only weakly related to the C/N ratio of the organic soil layer. The survey data for soil are probably too coarse in scale to pick up the expected relationship between nitrate leaching and C/N in soil. These deposition, soil and water data can be used to assess the risk of future N leaching given scenarios of constant N deposition and climate change. The results show that continued accumulation of deposited N in the organic soil will increase the risk for NO_3 leaching, and the risk further increases if climate change with increased temperature entails a decrease in the C stored in the soil.

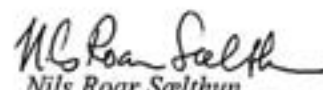
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Naturens Tålegrenser

Fagrappport nr. 102

**Risk of N leaching from forests to surface waters in
Norway**

Richard F. Wright

Preface

This work was supported in part by “Naturens tålegrenser” through contract number 981880 with SFT (Norwegian Pollution Control Authority) and in part by the EU-project DYNAMO (Commission of European Communities contract no. ENV4-CT95-0030). Participating in the project were Christian Nellemann (NIJOS) (responsible for the soils data), Arne Henriksen (NIVA) (responsible for the critical loads database), Brit Lisa Skjelkvåle (NIVA) (responsible for the water data) and Ann Kristin Buan (NIVA) (responsible for data analysis and preparation of maps). I thank Rachel Helliwell of the Macaulay Land Use Research Institute, Scotland, for suggesting the scoring system for the risk assessment.

Oslo, February 1998

Richard F. Wright

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Summary

Data from coniferous forests in Europe show a clear relationship between input and output of inorganic N ($\text{NO}_x + \text{NH}_y$) over a wide range of N deposition. The C/N ratio of the forest floor (organic soil layer) is the site factor that explains an additional fraction of the variation in NO_3 leaching. These relationships provide a basis for assessing the risk of N leaching to lakes in forested areas of Norway.

Necessary information is the C/N ratio in the organic layer of soil, N deposition and present-day nitrate concentrations and fluxes in lakes. Such data are part of the critical load database, maintained by the National Focal Centre at NIVA. The soils data come from surveys conducted by NIJOS, deposition data from NILU, and surface water chemistry data from NIVA. The database comprises values for each square within a 12x12 km grid.

Deposition is highest in southernmost, moderate in eastern and western, and lowest in central and northern Norway. Concentrations of NO_3 in lakewater in forested areas show a similar pattern. The C/N ratio of the organic horizon of forest soils, however, does not show this pattern. Decades of inorganic N deposition, most of which is retained in the soil, should lead to lower C/N ratios. But the tendency for soils in southernmost Norway to have higher C contents masks the effect of N retention.

Stepwise multiple linear regression of NO_3 concentration in lakewater on N deposition and C/N ratio in the organic soil horizon gives the following relationship:

$$\text{NO}_3 \text{ lake } (\mu\text{mol/l}) = 0.5 + 0.88 \text{ N deposition } (\text{mmol/m}^2) - 0.04 \text{ C/N g/g}$$

where $n = 634$, $r^2 = 0.33$, $p < 0.0001$.

The relatively weak correlation between C/N ratio and out/in ratio is probably due to the difficulty in determining a C/N ratio representative for the entire catchment. The soil samples are taken from discrete points at 9 km intervals, whereas the lakewater integrates runoff over entire catchments of hectares to several km^2 . Soils are notoriously heterogeneous, and chemical characteristics can vary widely within distances of only meters. Thus there is no assurance that soil collected at one point in a catchment, or in an adjacent area, will have a C/N ratio representative for the lake catchment.

Furthermore it is likely that within a given catchment N leaching probably occurs first at some discrete areas. Since most of the incoming N is retained in the catchment, the NO_3 reaching the lake may originate from only a small fraction of the catchment soils.

From the empirical relationships between nitrate concentration in lakes, N deposition and C/N ratio in forest soils, an estimate of risk of NO_3 leaching can be made for each grid square. High risk sites are those with high N deposition, low C/N ratio, and high output/input ratio. A score for risk of NO_3 leaching at each grid square is the sum of these 3 factors.

Two scenarios were evaluated in this assessment of risk of NO_3 leaching.

Scenario 1 entails 50 years of N deposition at present-day levels, with evaluation of nitrate leaching in the year 2040.

Scenario 2 entails constant N deposition plus climate change using results from the CLIMEX project, with evaluation of NO_3 leaching in the year 2040.

Under *scenario 1* continued inputs of N for 50 years at present-day rates with retention in the soil results in an increase in the amount of N stored in the soil. Assuming that all of this N is stored in the organic horizon and that the C content does not change, then the C/N ratio decreases, and the risk of N leaching increases. Under *scenario 2* the effect of climate change in addition to constant N deposition causes a relatively minor additional increase in risk.

1. Introduction

Current negotiations for reducing emission of sulphur and nitrogen compounds to the atmosphere are based on the critical loads concept. The goal is to close the gap between current deposition of acidifying compounds and the critical load of sensitive ecosystems. For surface waters the first-order acidity balance (FAB) model is used to calculate critical loads (Posch et al. 1995; Posch et al. 1997). The FAB model takes a static approach, and assumes that deposited inorganic nitrogen not taken up in vegetation and removed from the system, denitrified or taken up in the terrestrial ecosystem is released to runoff mainly in the form of nitrate. An additional fraction of nitrogen may be retained in the lake or lost by denitrification. For Norway this is a “worst case” in that nitrogen retention is currently much higher, mostly due to microbial immobilisation and retention in the catchment soil. Few lakes have concentrations of inorganic nitrogen more than about 30% of that deposited from the atmosphere (Henriksen and Brakke 1988; Kaste 1998; Skjelkvåle et al. 1996).

Input-output data from intensively-studied coniferous forest plots and catchments throughout Europe show a clear relationship between deposition and leaching of inorganic N ($\text{NO}_x + \text{NH}_y$) over a wide range of N deposition (Figure 1) (Dise and Wright 1995). The data indicate a minimum threshold for N deposition of about 9 kgN/ha/yr (about 65 mmol/m²/yr) below which very little N is leached and a maximum threshold of about 25 kgN/ha/yr (about 175 mmol/m²/yr) above which all sites show significant leaching. In the transition range the fraction N leached varies widely.

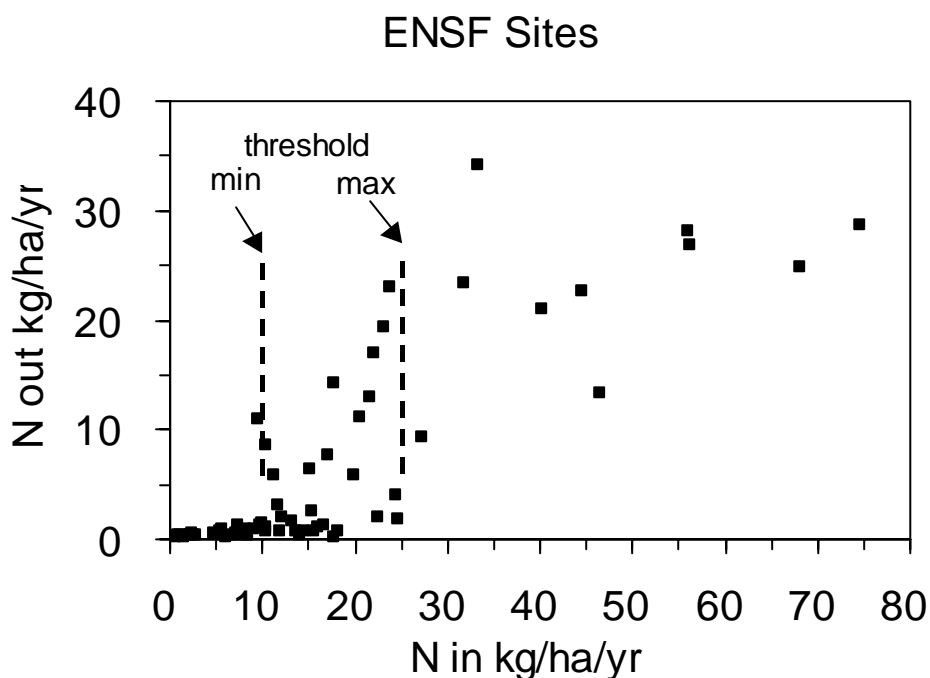


Figure 1. Relationship between deposition of inorganic nitrogen in throughfall and output in soil leachate below the rooting zone at 65 forested plots and catchments in Europe. Also shown are the minimum threshold below which leaching is insignificant and the maximum threshold at which leaching is significant at all sites (from Dise and Wright 1995).

This same pattern is found for lakes in Norway. Lakes in areas with high N deposition generally have higher concentrations of nitrate (Figure 2) (Henriksen and Brakke 1988; Skjelkvåle et al. 1996). This implies that chronic high deposition of nitrogen leads to increased leaching of inorganic nitrogen (mostly in the form of nitrate).

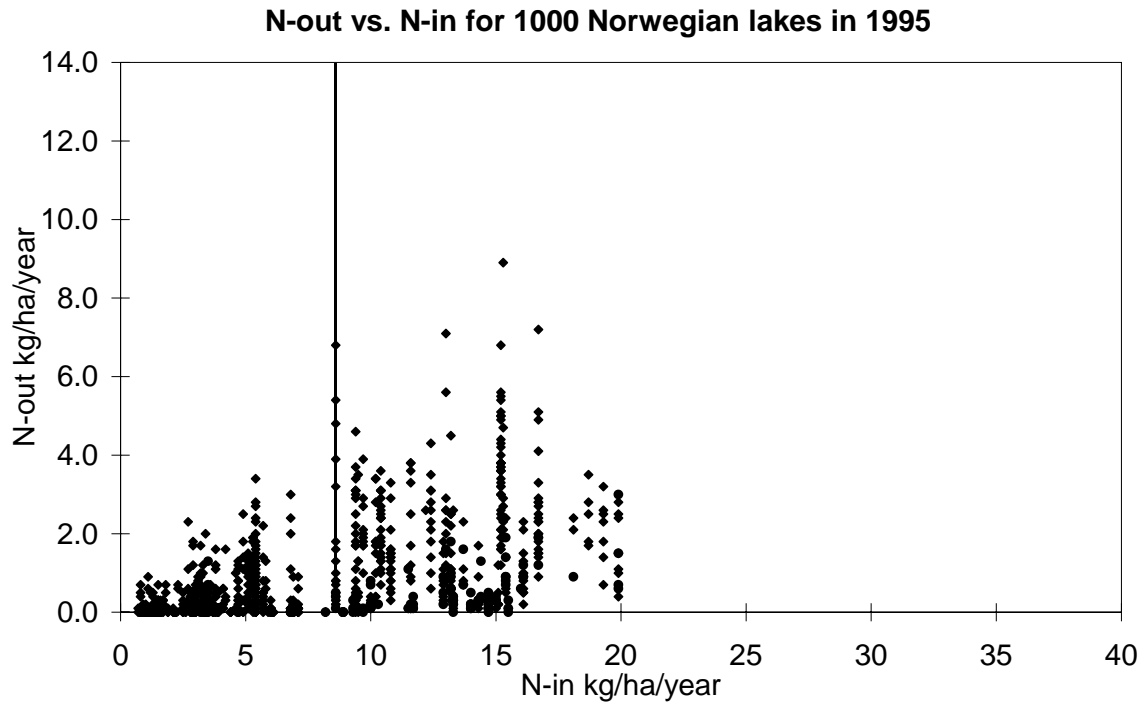


Figure 2. Relationship between deposition and runoff of inorganic N at 1000 Norwegian lakes sampled in 1995. The vertical line shows the minimum threshold of 9 kgN/ha/yr (65 mmol/m²/yr). From (Skjelkvåle et al. 1996).

The wide variation between sites in the fraction leached at a given N deposition is probably due to site-specific characteristics related to the nitrogen cycle. A systematic study of data from the 65 European forest sites indicates that the C/N ratio of the forest floor (organic soil layer) is the single site factor that explains a significant fraction of the variation in nitrate leaching (Figure 3) (Dise et al. 1998; Gundersen et al. 1998a). At sites with lower C/N ratios (i.e. more nitrogen per unit carbon) a greater fraction of deposited N is lost in leachate. Similar relationships are shown by the long-term large-scale experiments with nitrogen addition and removal (NITREX project) Tietema et al. 1998).

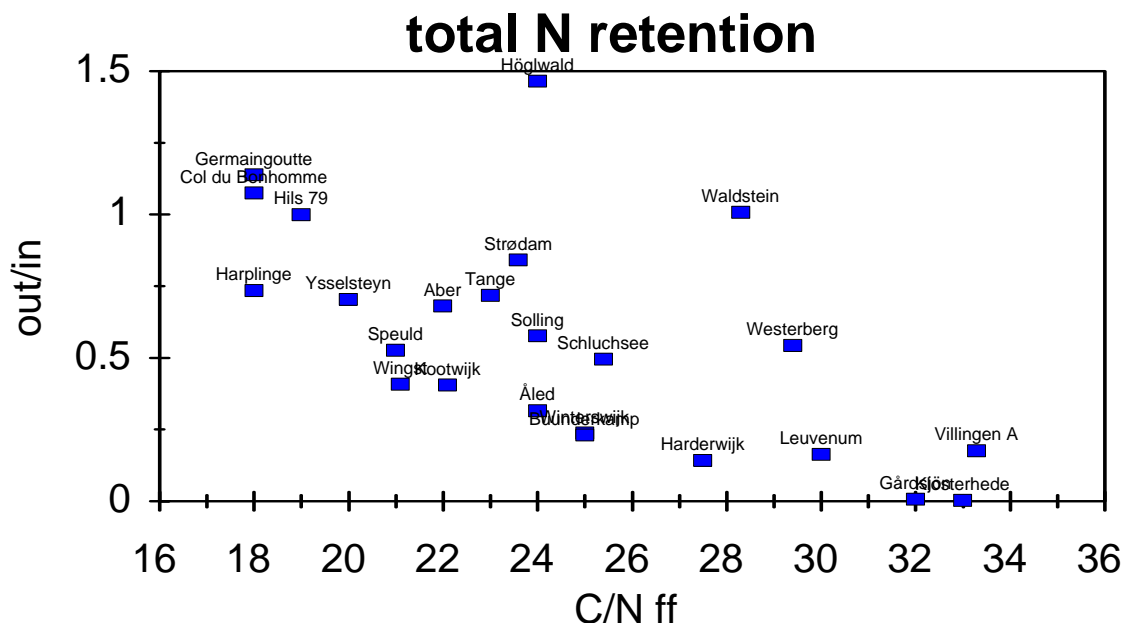


Figure 3. Relationship between fraction of N leached (out/in) to C/N (g/g) in forest floor at forest stands and catchments in Europe (after Gundersen et al. 1998a).

These relationships provide a basis for assessing the risk of N leaching in the future for lakes in forested areas of Norway. Necessary information is the C/N ratio in the organic layer of soil, N deposition and present-day nitrate concentrations and fluxes in lakes. For Norway such data are part of the critical load database, maintained by the National Focal Centre at NIVA. The soils data come from soil surveys conducted by the Norwegian Institute for Soil and Forest Monitoring (NIJOS), deposition data from the Norwegian Institute for Air Research (NILU) and surface water chemistry data from NIVA. The critical load database comprises values for each square within a 12x12 km grid in Norway.

2. Material and methods

2.1 Data

The soils, forest productivity, deposition and surface water chemistry data have been used previously to calculate critical loads for forest soils in Norway (Frogner et al. 1993; Frogner et al. 1994) and the data and aggregation procedures are described in these reports.

2.1.1 NIJOS soils data

During the period 1988-1992 NIJOS (Norsk Institutt for Jord- og Skogkartlegging, The Norwegian Institute for Land Inventory) conducted a systematic survey of forest soils on a countrywide network. This survey was part of a monitoring programme (“Overvåking av skogens sunnhetstilstand”, The

Monitoring of Forest Health Program) which is part of the International Co-operative Programme for Monitoring of Forest Damage under the United Nations Environment Programme and the United Nations Economic Commission for Europe. A total of 933 permanent plots in coniferous forest are located at each cross-point on a 9x9 km grid placed over the entire country (Esser and Nyborg 1992). In addition 122 permanent plots in birch forest are located at each cross-point on a 18x18 km grid (Esser 1994). At each plot a soil pit was dug, the soils were described, and samples collected for chemical analysis from each horizon. Sampling and analysis details are given by Esser (1994) and Esser and Nyborg (1992).

The soils data are on a 9x9 (or 18x18) km grid, whereas the Norwegian critical loads database is on a 12x12 km grid. The soils data were thus converted to the 12x12 km grid. In the event that more than one soil sample fell within a 12x12 km grid square the mass-weighted mean of the samples was used. Soils data cover 720 of the total 2315 grid squares on land area in Norway.

The soil data is by horizon. The forest floor (organic horizon) is assumed to consist of horizons described as LHF, LH, L, H, F, or O. These were mass-weighted to obtain one value for contents of C and N in mol/m² and C/N g/g for the organic horizon of each profile.

2.1.2 NIJOS forest productivity data

The NIJOS monitoring programme also includes estimates of productivity for each of the 933 plots in coniferous forest. At each plot annual maximum yield in m³/ha/yr is estimated. Yield capacity for a given site quality class and tree species is defined as the maximum mean annual increment for an established stand of high density and which is thinned to obtain maximum stem harvest. Actual yield (and increment) will be lower. The values were thus scaled by factor 0.4 in western Norway to 0.7 in eastern Norway (Frogner et al. 1993). Annual uptake of base cations and N was calculated from the annual increment and typical concentrations in stems and bark (Table 1).

Table 1. Concentrations of base cations and nitrogen (% dry weight) in stem and bark of coniferous trees used to calculate annual net uptake (from Frogner et al. 1993).

Element	Concentration %
Ca	.15
Mg	.09
K	.06
N	.34

2.1.3 Deposition

Tørseth and Pedersen (1994) have calculated a weighted-average total deposition value for each 50x50 km NILU-grid (a 3 by 3 sub-division of an EMEP-grid) from ambient air concentrations and wet deposition taking into account land-use data (coverage of different receptors). Weighted-means for the 5-year period 1988-1992 were used. The deposition values for each 12x12 grid square was estimated from the NILU-grids (Henriksen 1998).

2.1.4 Surface water

The chemistry of surface water within each 12x12 km grid square was based largely on the national lake surveys conducted in 1986 and 1995. The chemistry of lakes within each grid square was evaluated subjectively and the value judged most typical chosen to represent the grid. If there were large variation among lakes within a grid, the most sensitive lake was selected if it represented more

than 25% of the grid area. The database was last updated in October 1996. Details are given by Henriksen (1998).

2.2 Scenarios

Two scenarios were evaluated in this assessment of risk of nitrate leaching.

Scenario 1 entails 50 years of nitrogen deposition at present-day levels, with evaluation of nitrate leaching in the year 2040.

Scenario 2 entails constant N deposition plus climate change using results from the CLIMEX project, with evaluation of nitrate leaching in the year 2040. CLIMEX indicated that mean annual temperature elevated by 3.7°C causes increased decomposition of old soil organic matter with net loss of about 1 molC/m²/yr and release of the nitrogen as nitrate to soil solution (Wright 1998; Wright et al. 1998). The increase in mean annual temperature of 3.7°C lies in the range of predicted values for 60°N latitude for about 50-100 years in the future given only moderate decrease in emission of greenhouse gases. For this scenario the climate change effect was assumed to increase linearly from 0 in year 1990 to 1 in year 2040. Thus the C pool was assumed to decrease by 0 mol/m²/yr in year 1990 and 1 mol/m²/yr in the year 2040 with linear increase between. The nitrogen contained in the decomposed organic matter was assumed to behave as N from deposition; the fraction retained in the soil was regulated by the C/N ratio.

3. Results and discussion

3.1 Status in 1990

The map of deposition of inorganic N to forested areas of Norway for the period 1988-92 shows that deposition is highest in southernmost Norway, moderate in eastern and western Norway and low in central in northern Norway (Figure 4) (Tørseth and Pedersen 1994).

Concentrations of nitrate in lakewater in forested areas show a similar pattern, with the highest concentrations generally found in southernmost and southeastern Norway (Figure 5) (Skjelkvåle et al. 1996).

The C/N ratio of the organic horizon of forest soils, however, does not show this pattern (Figure 6). Decades of inorganic nitrogen deposition, most of which is retained in the terrestrial soils, should lead to lower C/N ratios. This might be offset by an accumulation of carbon over the same time, i.e. more nitrogen stored but at the same C/N ratio. The data do not indicate significantly more C in organic soil horizons in soils in areas receiving higher N deposition (Figure 7).

There is no *a priori* reason to believe that Norwegian forest ecosystems should not respond to nitrogen deposition in a manner similar to that shown by the coniferous forest stands in Europe analysed by Gundersen et al. 1998a. Their data indicate that chronic elevated nitrogen deposition causes lower C/N ratios in the forest floor. Data from the European NITREX experiments and similar experiments in forests in the eastern United States show that most of the added nitrogen is retained in the soil, and only a small fraction goes to vegetation (Gundersen et al. 1998b; Nadelhoffer et al. 1999). Unless the carbon pool increases commensurately, this retention of nitrogen must lead to lower C/N ratios.

N - deposition, observed 1990

in deciduous- and coniferous forest

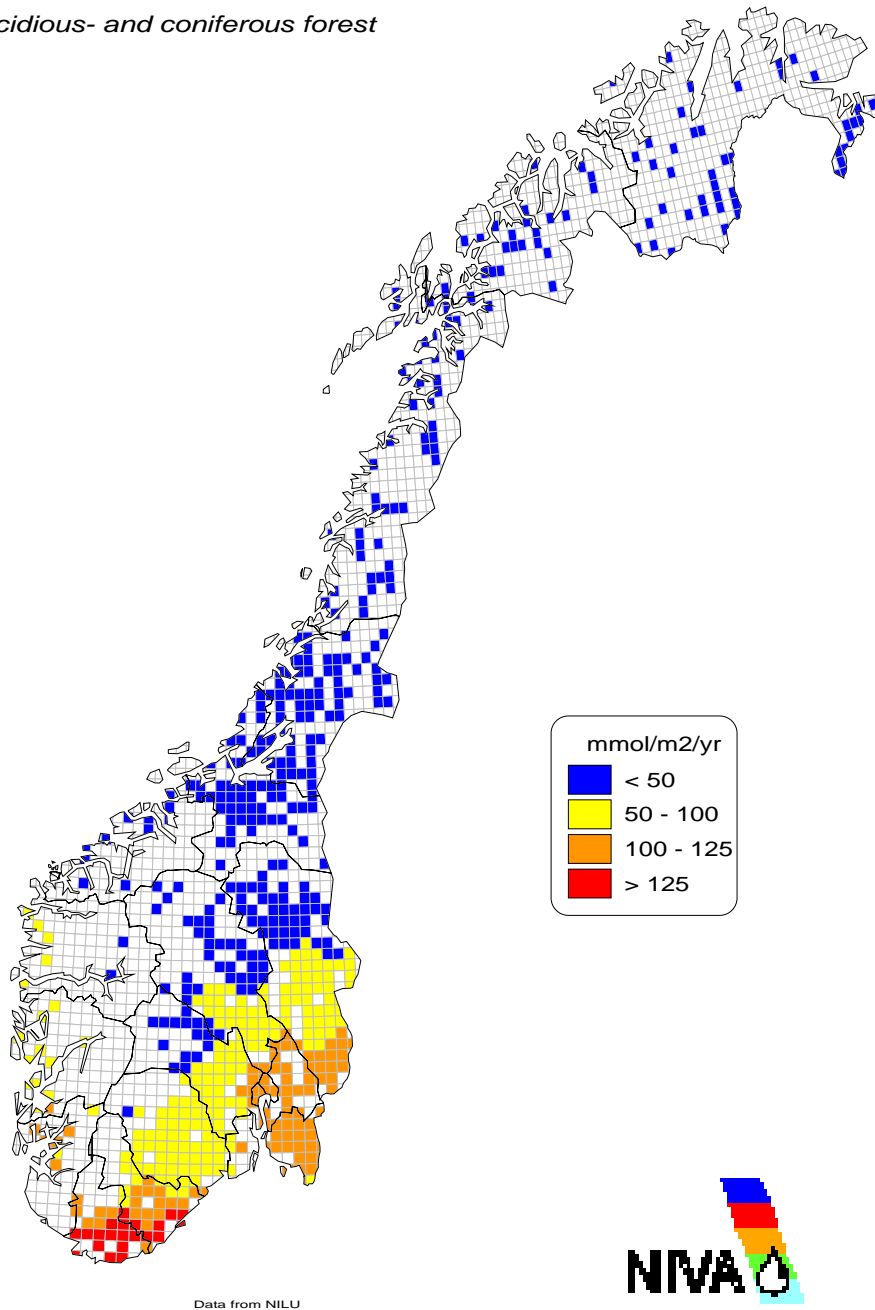


Figure 4. Map of Norway showing deposition of inorganic N (NO_x + NH_y) to grid squares with forest. Data from Tørseth and Pedersen (1994).

NO₃ (lakewater), observed 1990

in deciduous- and coniferous forest

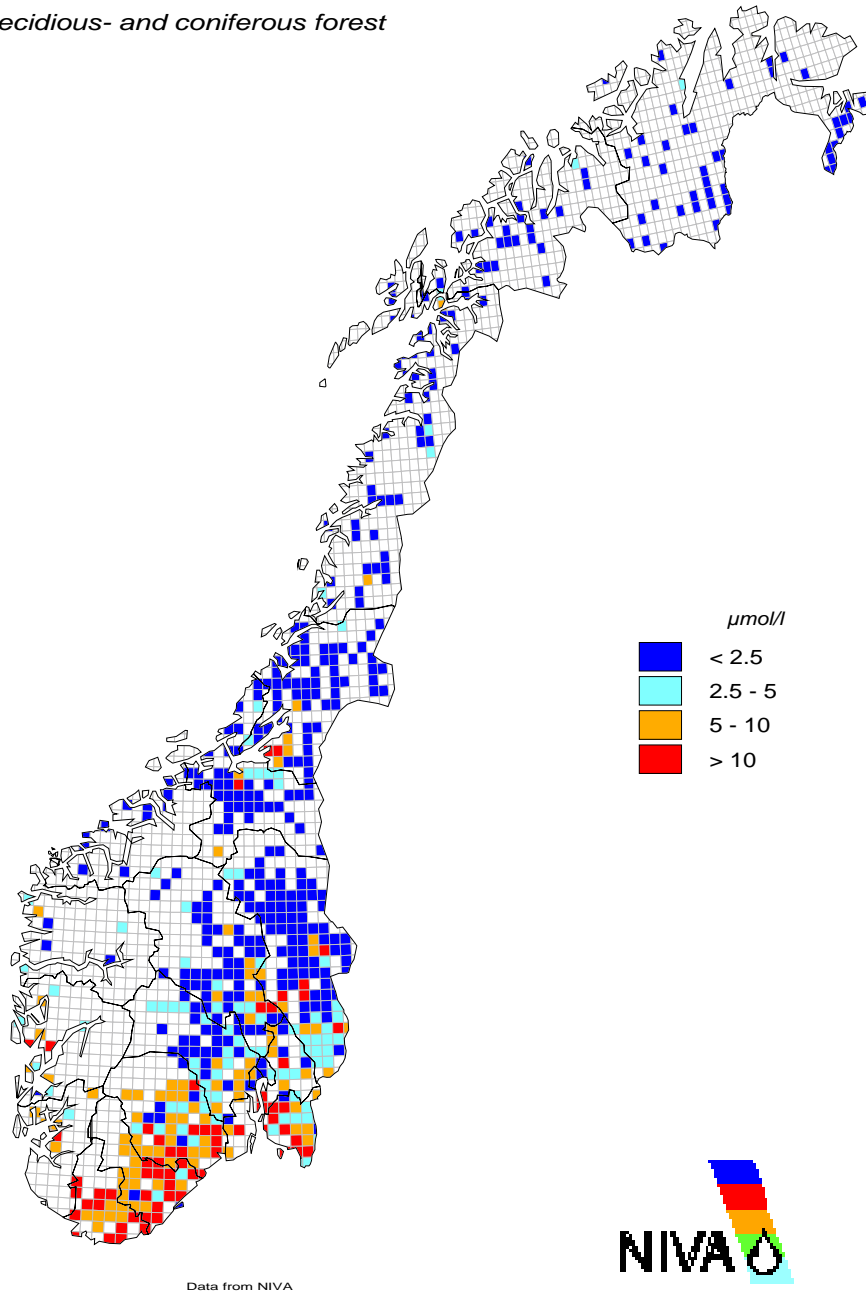


Figure 5. Map of Norway showing concentrations of nitrate in lakewater in forested areas. Data from Skjelkvåle et al. (1996).

C/N - ratios

in deciduous- and coniferous forest, organic horizon

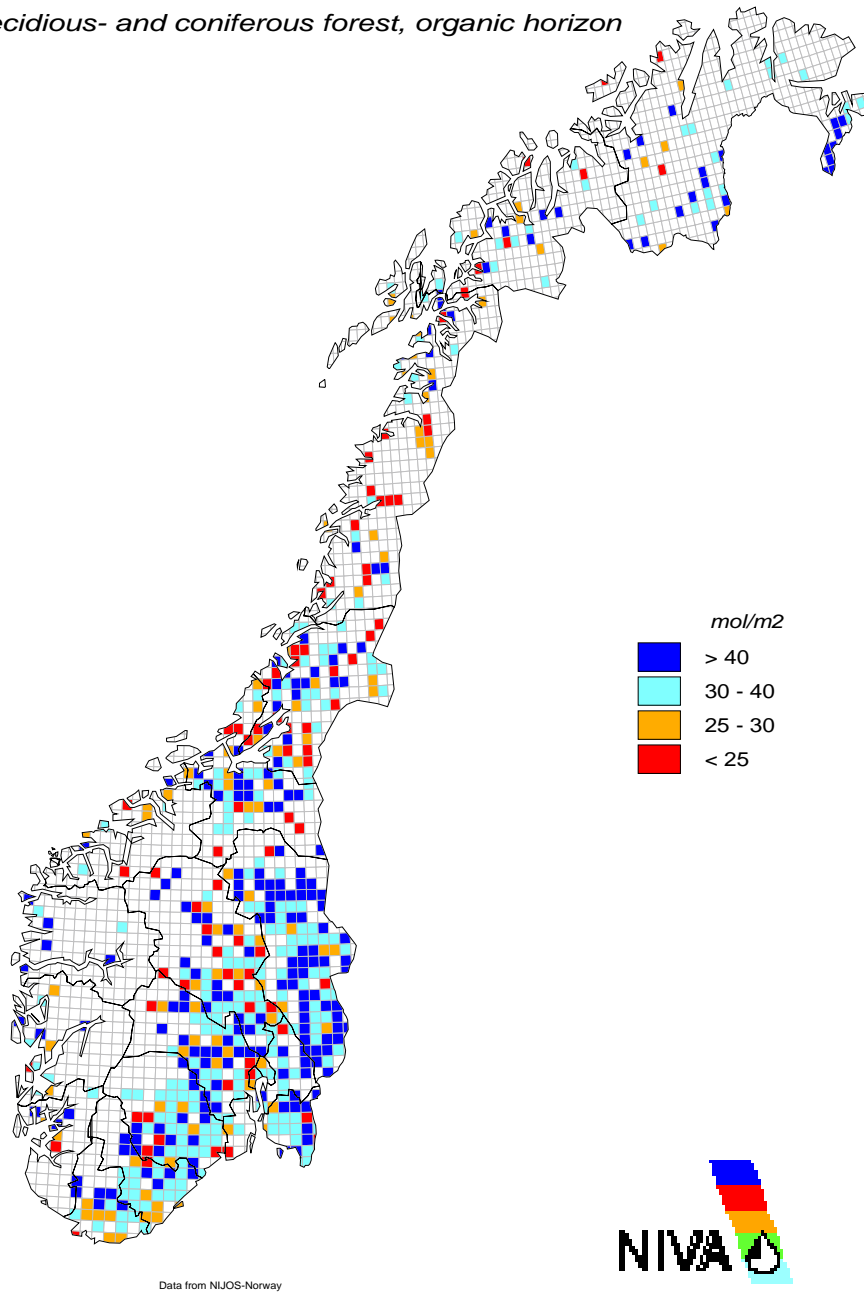


Figure 6. C/N ratio (g/g) in the organic horizon of forest soils in Norway. Data from Esser and Nyborg (1992) and Esser (1994).

Organic C

in deciduous- and coniferous forest, organic horizon

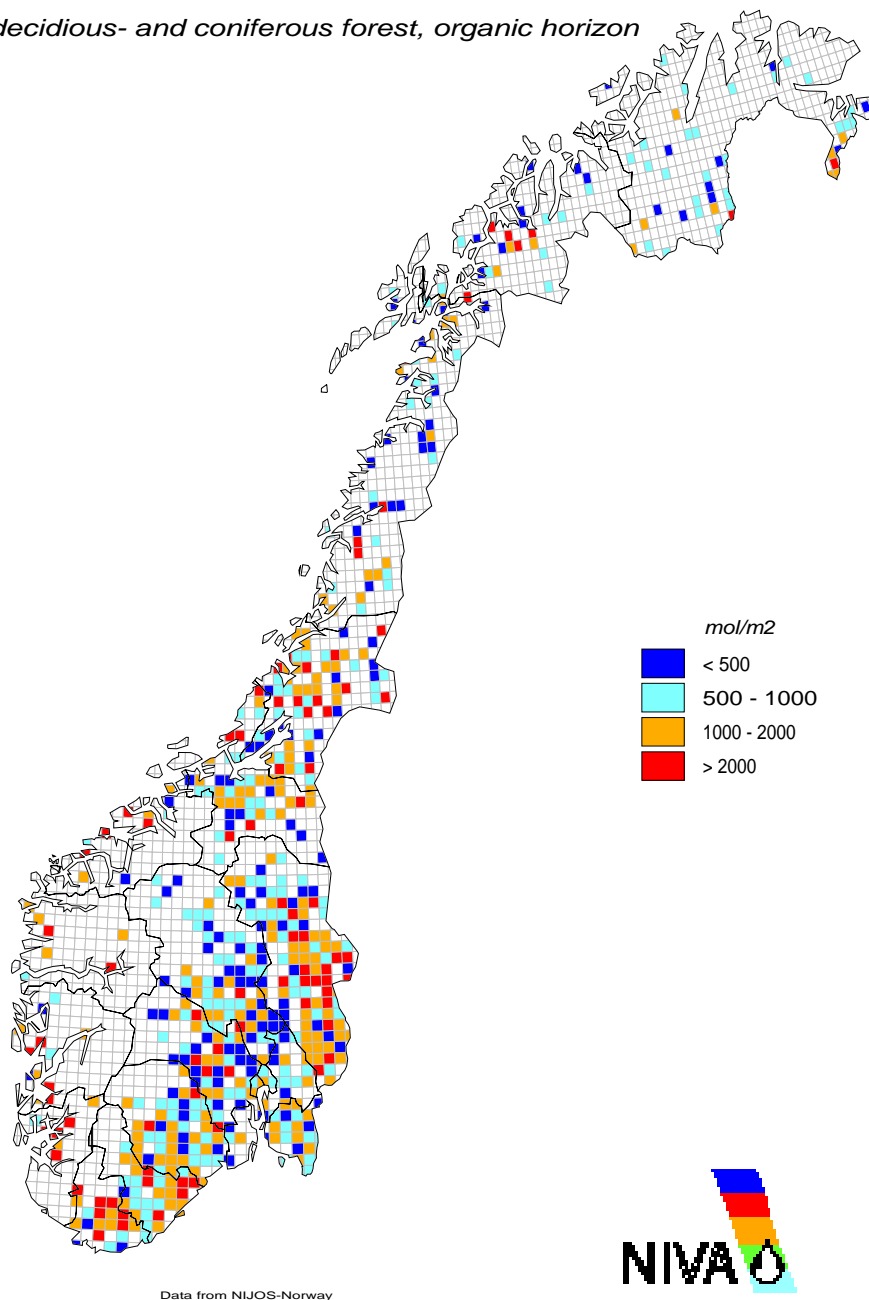


Figure 7. Carbon content of the organic horizon of forest soils in Norway. Data from Esser and Nyborg (1992) and Esser (1994).

Retention of N inputs at rates typical for large areas of southern Norway should cause significant lowering of C/N ratios in the organic soil horizon in the course of only a few decades. For example for 50 years of N deposition and retention of 100 mmol/m²/yr is sufficient to lower the C/N ratio from 26 to 22 g/g to of an organic soil with a C pool of 1000 mol/m². From the empirical input/output relationship of Gundersen et al. (1998a), this would imply an increase in fraction N leached from about 0.2 to about 0.5 (Figure 3).

That lower C/N ratios should lead to lower retention of nitrogen deposition follows from studies of nitrogen transformation processes in forest ecosystems. For example, a study of mineralisation of soil nitrogen at 600 deciduous forest sites in southern Sweden showed that net nitrogen mineralisation and nitrification were highest in regions receiving highest N deposition and were related to both soil pH and to soil C/N (Falkengren-Grerup et al. 1998).

The relationship between input and output for lakes in forest areas of Norway shows the pattern familiar from the 65 forest stands in Europe, although the European sites span a much larger gradient in N deposition (Figure 8) (Dise and Wright 1995). The scatter of points is triangular, with no points occurring above the 1:1 line. This strongly indicates that N input is a necessary but not sufficient factor for N leaching.

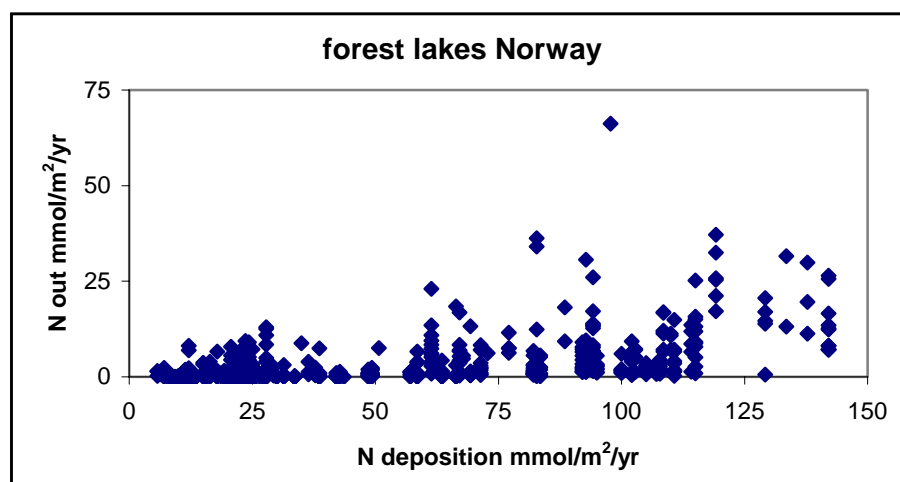


Figure 8. Deposition and runoff of inorganic N at forest lakes in Norway. Runoff is calculated from N concentrations in the lake times the annual mean specific runoff. Inputs are generally about ½ as oxidised and ½ as reduced nitrogen, whereas output is almost entirely as NO₃. Data from NILU (Tørseth and Pedersen 1994) and NIVA (Skjelkvåle et al. 1996).

There is only a very weak relationship between the fraction of N leached (output/input) and the C/N ratio of the organic horizon (Figure 9). The scatter plot indicates a slight tendency to higher leaching in soils with C/N ratios below about 25. Most of the soils have C/N ratios well above 30. Since high C/N ratios indicate N deficient systems, no significant leaching is expected from such soils (Gundersen et al. 1998a).

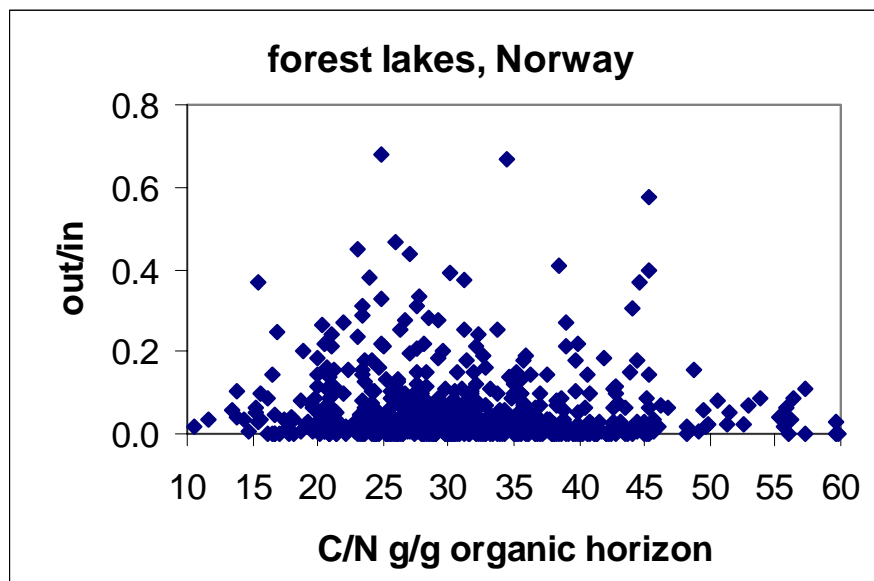


Figure 9. Fraction of deposited inorganic N lost to runoff (out/in) and C/N ratio in organic soil horizon for 12x12 km grid squares in forested areas of Norway. Deposition data from NILU (Tørseth and Pedersen 1994), runoff data from NIVA (Skjelkvåle et al. 1996), and soils data from NIJOS (Esser 1994; Esser and Nyborg 1992).

Stepwise multiple linear regression of NO₃ concentration in lake water on N deposition and C/N ratio in the organic soil horizon gives the following relationship:

$$\text{NO}_3 \text{ lake } (\mu\text{mol/l}) = 0.5 + 0.88 \text{ N deposition } (\text{mmol/m}^2) - 0.04 \text{ C/N g/g}$$

where $n = 634$, $r^2 = 0.33$, $p < 0.0001$.

The most likely reason for the relatively weak correlation between C/N ratio and out/in ratio probably lies in the determination of a C/N ratio representative for the entire terrestrial catchment to the lake. At the European sites of Gundersen et al. (1998a), the soil and soil solution are sampled at the same point. In contrast in the Norwegian survey the soil samples are taken from discrete points at 9 km intervals, whereas the lake water integrates runoff over entire catchments of hectares to several km² area. Soils are notoriously heterogeneous, and chemical characteristics can vary widely within distances of only meters. Thus there is no assurance that soil collected at one point in a catchment, or in an adjacent area, will have a C/N ratio representative for the lake catchment.

Furthermore it is likely that within a given catchment N leaching probably occurs first at some discrete areas. Since most of the incoming N is retained in the catchment, most of the nitrate reaching the lake may originate from only a small fraction of the catchment soils. This is the case at the NITREX catchment at Gårdsjön, Sweden, where soil solution shows large spatial and temporal variations within the catchment, and the nitrate measured in runoff can be explained by leaching from a small fraction of the catchment area (Stuanes and Kjønås 1998).

3.2 Risk of nitrate leaching

From the empirical relationships between nitrate concentration in lakes, N deposition and C/N ratio in forest soils, an estimate of risk of nitrate leaching can be made for each grid square. High risk sites are those with high N deposition and low C/N ratio. In addition the flux ratio of output/input was used,

where output flux was assumed equal to the lake nitrate concentration times the annual average runoff at each grid square. The reasoning here was that sites at which a significant fraction of deposited N is leached will have a higher risk of NO₃ leaching in the future, regardless of C/N ratio.

All three factors increase the risk of nitrate leaching. The cumulative sum can be schematically represented by giving each factor a score and then summing the scores for each grid square. Scoring criteria from 1-5 were arbitrarily chosen for 5 classes within each factor (Table 2).

Table 2. Scoring criteria used in development of N leaching risk assessment

soil C/N ratio g/g		N dep mmol/m ² /yr		out/in ratio	
class	score	class	score	class	score
>30	1	<30	1	<0.010	1
26-30	2	30-60	2	0.010-0.033	2
22-26	3	60-90	3	0.034-0.099	3
18-22	4	90-120	4	0.10-0.333	4
<18	5	>120	5	>0.333	5

On this basis there is a clear relationship between risk of nitrate leaching and concentrations of nitrate measured in 1990 in lakes in forested regions (Figure 10). At scores of 5 and below concentrations of nitrate were below about 5 µmol/l in all lakes, while at scores of 11 and above all lakes had concentrations above 5 µmol/l. The values of 5 and 11 are merely indicative and have no inherent meaning in themselves with respect to N processes or dose-response relationships.

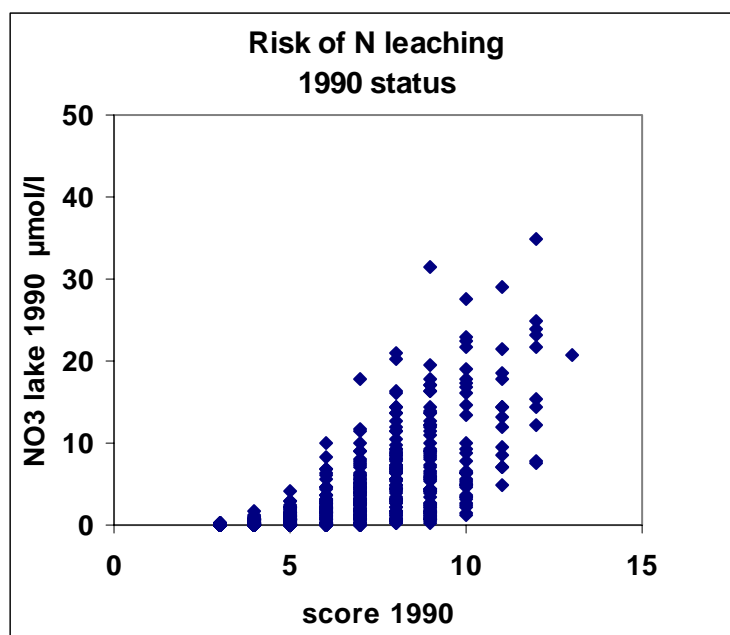


Figure 10. Measured nitrate concentration in lakewater and score for risk of N leaching in forested areas of Norway for the year 1990.

3.3 Evaluation of scenarios for the future

3.3.1 Scenario 1: constant N deposition

Continued inputs of nitrogen for 50 years at present-day rates with retention in the soil will result in an increase in the amount of N stored in the soil. Assuming that all of this N is stored in the organic horizon and that the carbon content does not change, then the C/N ratio will decrease in the future. And this will increase the risk of N leaching. Under this scenario the risk of N leaching increases for the majority of the grid squares (Figure 11).

This calculation takes into account net uptake of N in the forest with subsequent removal of N in the stems with forest harvest. For coniferous forest the net uptake is related to forest productivity. For birch forests it is assumed that there is no net removal of N and thus no net uptake.

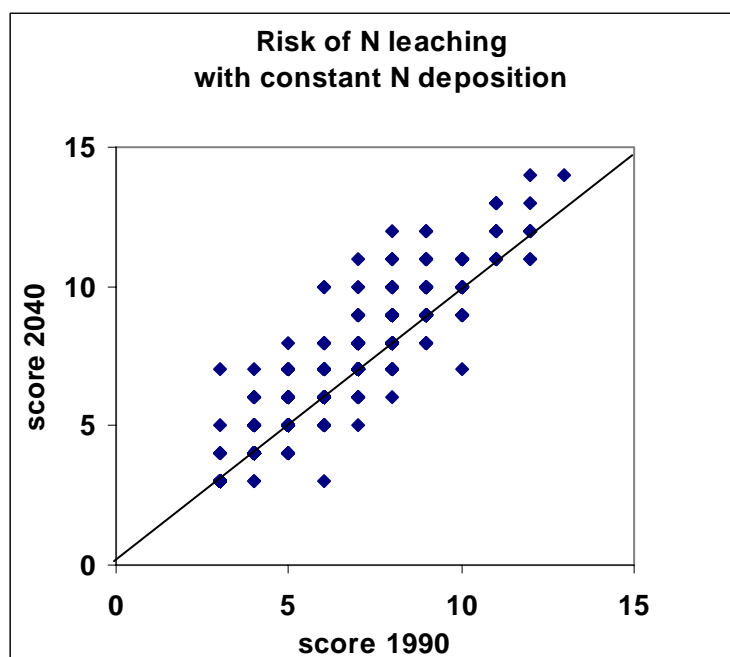


Figure 11. Risk of N leaching in the year 2040 under the scenario with constant N deposition as compared with risk in 1990.

3.3.2 Scenario 2: constant N deposition plus climate change

Under this scenario the C pool in the organic soil horizon is assumed to gradually decrease due to an increase in mean annual temperature. The annual decrease in C pool for full climate change of 3.7°C is taken as the value measured over 4 years of the CLIMEX experiment. N deposition is assumed to remain constant at present-day levels, and N removal in tree harvesting is assumed to be the same as for scenario 1.

The change in the C pool caused by this climate change is relatively minor. The C pool in the organic horizon at most sites is 500-1500 molC/m² (Figure 7). Over 50 years with gradually increasing climate change, the CLIMEX data indicate that the C pool decreases only by about 25 molC/m². Nevertheless there appears to be a slightly larger risk of N leaching under this scenario (Figure 12).

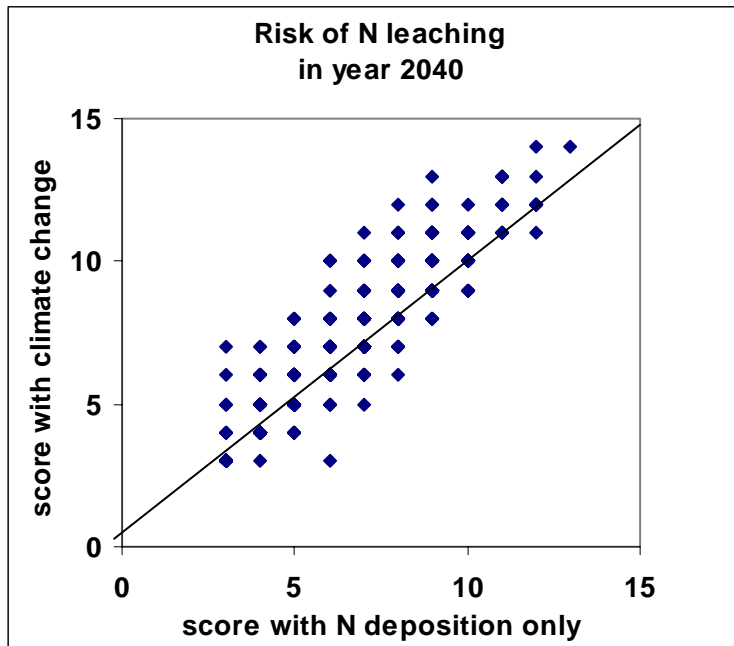


Figure 12. Risk of N leaching in the year 2040 under the scenario with climate change as compared with the scenario with constant N deposition.

Thus relative to present-day 1990 the frequency of grid squares with high risk of N leaching (> 10) is larger for the year 2040 due to the continued N deposition and accumulation of N in the soil (scenario 1), and even larger under the combined conditions of continued N deposition and climate change (Figure 13).

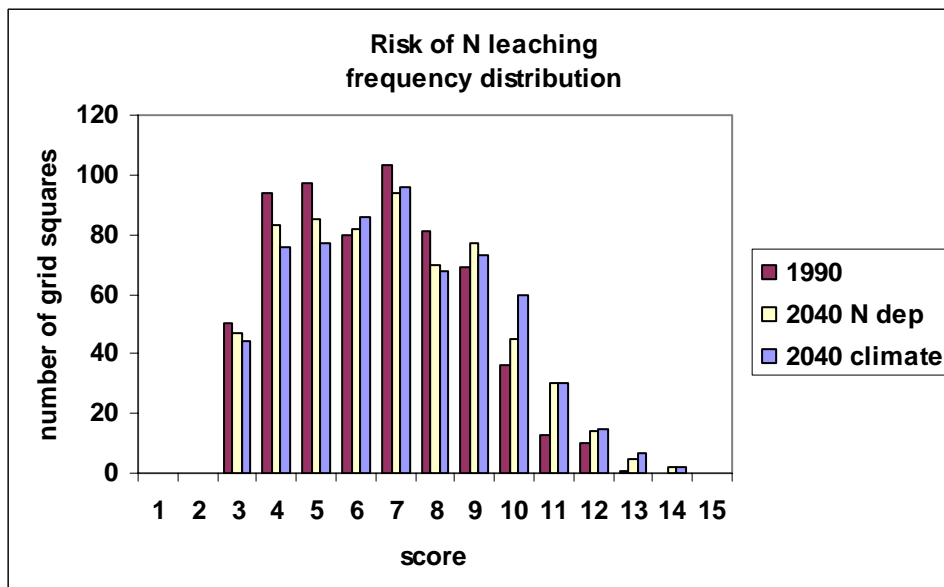


Figure 13. Frequency histogram of scores for risk of N leaching at grid squares in forested areas of Norway for the present-day situation (1990), and two scenarios for the year 2040.

Risk of N - leaching

Score 1990

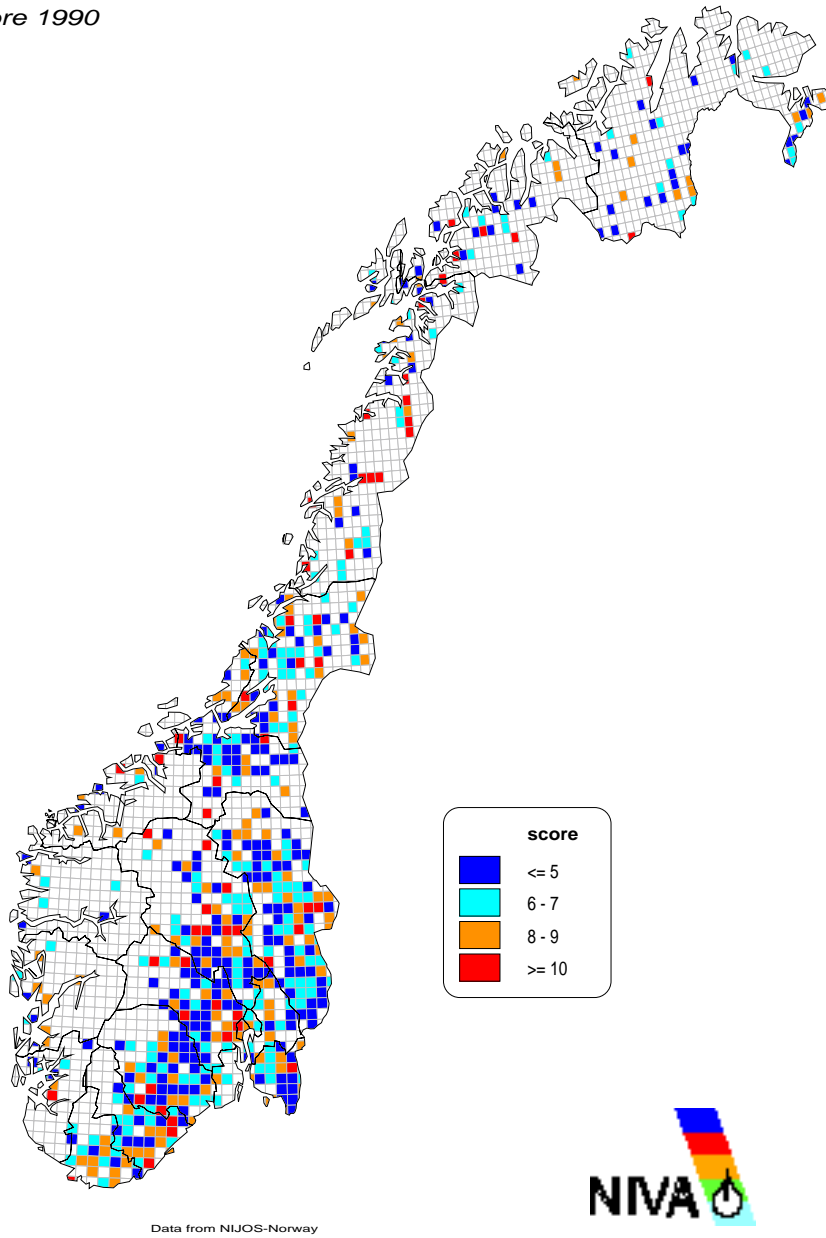
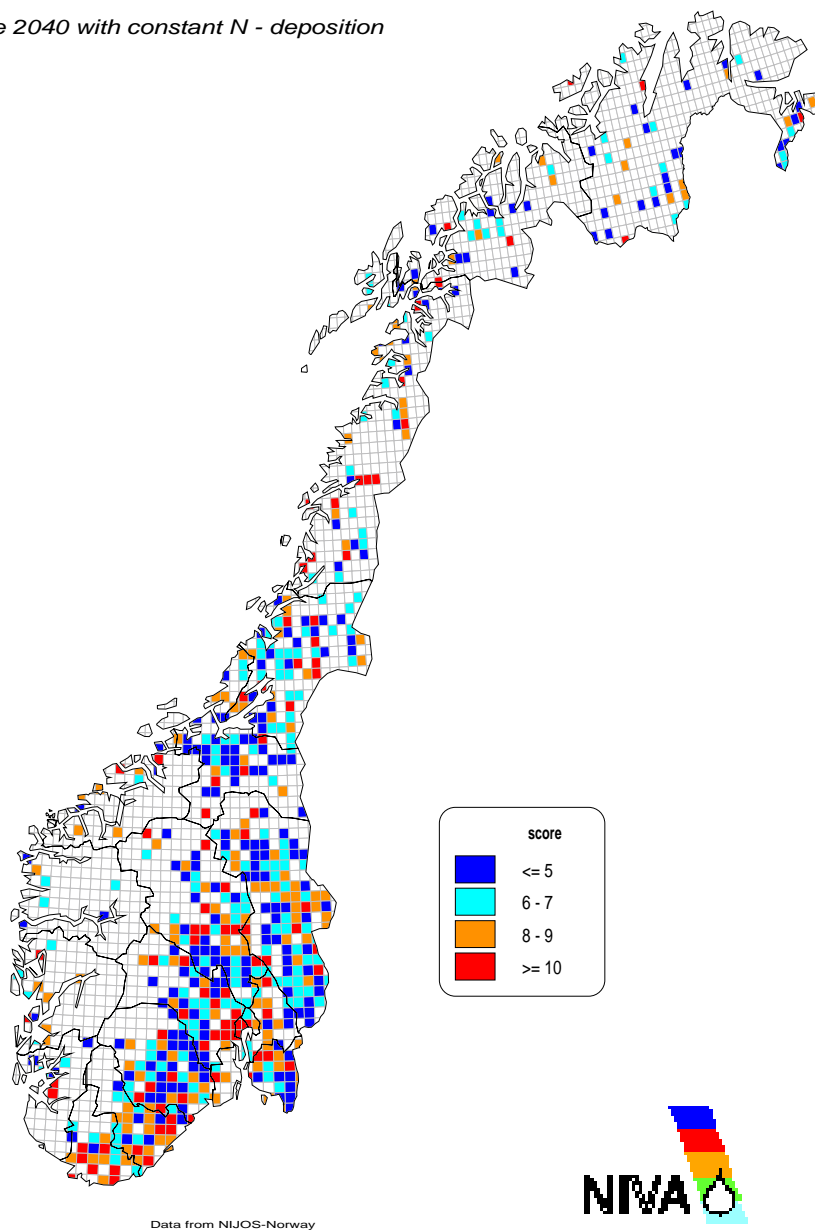


Figure 14. Map of risk of N leaching in forest areas of Norway for the year 1990.

Risk of N - leaching

Score 2040 with constant N - deposition



Data from NIJOS-Norway

Figure 15. Map of risk of N leaching in forest areas of Norway for the year 2040 with constant N deposition.

Risk of N - leaching

Score 2040 with constant N - deposition plus climate change

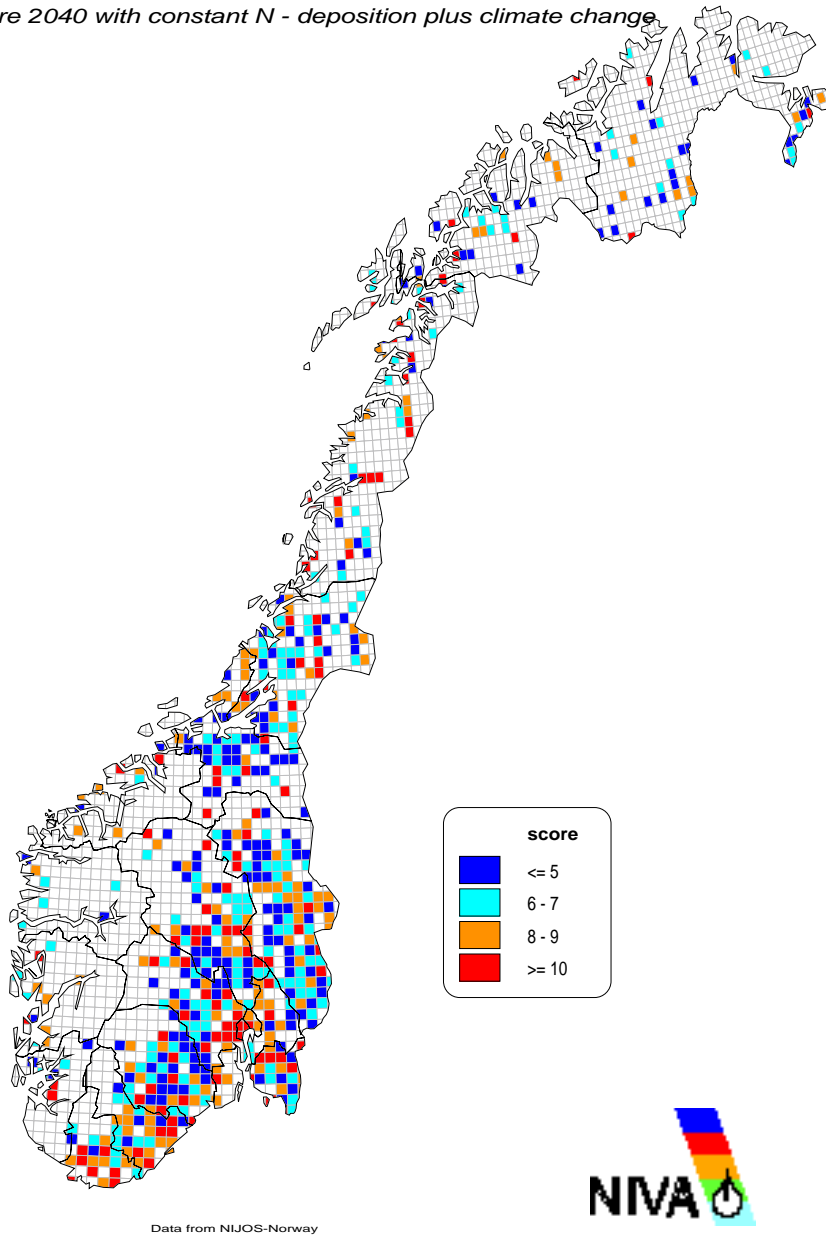


Figure 16. Map of risk of N leaching in forest areas of Norway for the year 2040 with constant N deposition plus climate change.

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Appendix A. Naturens Tålegrenser - Oversikt over utgitte rapporter

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