
Miljøverndepartementet

FAGRAPPOR NR. 33

Map of critical loads
for coniferous forest soils in
Norway

Norwegian Forest Research Institute NISK
Norwegian Institute for Water Research NIVA
Norwegian Institute for Land Inventory NIJOS

Naturens Tålegrenser

Programmet Naturens Tålegrenser ble satt igang høsten 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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Abstract:

Maps of critical loads of acidity and exceedance (sulphur) for coniferous forest soils in Norway have been compiled using the dynamic MAGIC model based on the soil survey data of NIJOS and NISK, the atmospheric deposition data of NILU, the forest productivity data of NIJOS, and the surface water chemistry data base of NIVA. The criterion used was that the Ca/Al molar ratio in soil solution should not fall beneath 1.0 in the uppermost 50 cm of soil. Scenarios were run 50 years into the future under the assumptions that nitrogen deposition and nitrogen retention are unchanged relative to the present. The results show that the critical load for soils is higher than the critical load for water (i.e. soils are less sensitive). Critical loads for soils are exceeded by present-day sulphur deposition in many squares in southernmost Norway. There are indications that crown density of spruce stands in these squares is also lower than in nearby squares in which the critical load is not exceeded.

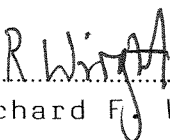
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**MAP OF CRITICAL LOADS (SULPHUR) FOR
CONIFEROUS FOREST SOILS IN
NORWAY**

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NORSK SAMMENDRAG

Begrepet tålegrenser må sees i sammenheng med at en ønsker å kvantifisere økosystemets toleranse overfor en belastning av forsurende komponenter som ikke medfører langvarige skadelige effekter på økosystemets struktur og funksjon. Tålegrenser er definert som **den høyeste belastning av forsurende komponenter som ikke vil gi skadelige effekter på økosystemets struktur og funksjon**. Denne definisjonen kan anvendes på forskjellige reseptorer: *skog, jord, grunnvann og overflatevann*.

Beregningen av tålegrensen for jord skjer i overensstemmelse med Manualen under "Langtransportkonvensjoner" og vil være et viktig grunnlag for forhandlinger som skal lede til en nye protokoller for utslippsbegrensninger for svovel og nitrogen i Europa. Kartlegging av tålegrensen for svovel omfatter ialt 29 nasjoner.

Arbeidet med å beregne tålegrenser for skogsjord i Norge er et samarbeidsprosjekt mellom Norsk institutt for skogforskning (NISK), Norsk institutt for vannforskning (NIVA) og Norsk institutt for jord- og skogkartlegging (NIJOS). Første fase av prosjektet har vært å samle inn tilgjengelige data som må til for beregninger av tålegrenser. Vi har tatt utgangspunkt i de jorddata som er innsamlet av "Overvåkingsprogram for skogskader" (OPS). Dette omfatter jorddata fra 1)- Landsomfattende representative registreringer som dekker 903 prøveflater i barskog over hele Norge og 2)- Spesielle intensive skogøkosystemanalyser. NIJOS startet innsamlingen av jordprøver i 1988 og i 1991 var alle flatene prøvetatt. NISK startet innsamlingen i 1986 og de siste overvåkingsflatene ble prøvetatt i 1989.

Viktige jordparametere som inngår i jorddatabasene er utbyttbare kationer, pH og tekstur. I tillegg er det foretatt totalkjemi og mineralogi på alle de intensivt overvåkte flatene og 60 flater i 9x9 nettet, ialt 90 flater. Totalkjemi er foretatt på 82 av flatene i 9x9 km nettet. For hver flate ble prøveprofilen beskrevet og klassifisert etter det kanadiske systemet.

Produksjonsevne er beregnet ut fra målt bonitet og alder på hver flate. Ut fra produksjonsevne er det beregnet et netto næringsopptak i trærne på hvert rutepunkt.

NILU og NIVA har i et rutenett på henholdsvis 50x50 km og 12x12 km beregnet gjennomsnittsverdier for atmosfæriske tilførsler og avrenning av vann og kjemiske hovedkomponenter. Ut fra disse databasene er det for hver 9x9 km rute beregnet en gjennomsnittlig atmosfærisk tilførsel og avrenning.

I arbeidet med å bestemme tålegrenser for jord ser vi både på de naturlige og antropogene syredannende og syrekonsumerende prosesser som på lang sikt vil gi endringer i jordas bufferkapasitet. Den tid det tar for å endre jordas bufferkapasitet på grunn av sure tilførsler kan dreie seg om tiår eller hundreår.

Vi har basert vårt arbeide med å kartlegge tålegrensen for svovel for skogsjord på to modeller. Den dynamiske modellen, MAGIC, er en typisk nedslagsfeltmodell og benytter gjennomsnittsparemetere på nedbørfeltnivå. Modellen fokuserer på

samspeilet mellom jordkjemi, vannkjemi og nedbørkjemi. Den statiske modellen, PROFILE, er basert på prinsippet om massebalanse. Modellen beregner forvitringen og tålegrensen for et jordprofil med flere sjikt. Nøkkelparametere er tekstur og mineralogi. I beregning av tålegrensen er jordybden satt lik 50 cm (=rotsonen). De tålegrenser som er beregnet gjelder svovel og det er forutsatt at belastning og igjenholdelse av nitrogen-forbindelser ikke endres.

Ved anvendelse av MAGIC-modellen ble det kjørt en optimaliseringsprosedyre for å bestemme den opprinnelige metningen og forvitringen av de fire basekationene i 1846. Modellen ble så kjørt for 140-års perioden fram til 1986 slik at den passet best mulig med dagens målte verdier for jordkjemi og overflatevann. Tålegrensen ble så beregnet under forutsetning av at belastningen brått ble endret til et nytt nivå av nedfall inntil kriteriet for jord i relasjon til skog, $Ca/Al=1$, og kriteriet for vann, alkalinitet på 20 og 50 uekv/l, ble nådd.

Ved anvendelse av PROFILE-modellen er beregning av tålegrensen basert på at prosesser som konsumerer og prosesser som produserer syrer i rotsonen (dybde = 50 cm) skal være i likevekt. Modellen inkluderer bare prosesser som er aktiv over en lengre tidsperiode (10-100 år). Tålegrensen er derfor en funksjon av tilførsel av basekationer med nedbøren, kjemisk forvitringshastighet og netto næringsopptak i trær.

Kartlegging av tålegrenser for skogsjord i Norge ved MAGIC og PROFILE viser at tålegrensen for skogsjord er lav sammenlignet med andre Europeiske land. Overskridelsene er størst i kystnære områder av Sør-Norge og lavest i innlandet. Ved dagens tilførsel av svovel er tålegrensen overskredet for store deler av Sør-Norge.

Skogsjordas bufferegenskaper vil i områder med tykt jordsmonn være helt avhengig av hvordan modellen avgrenser økosystemet. Fordi MAGIC er basert utfra et samspill mellom vannkjemi og jordkjemi og tar hensyn til forvitring i dypere jordlag (dybde >50 cm) vil MAGIC i områder med tykt jordsmonn beregne en større forvitring enn PROFILE, som beregner kun forvitringen for rotsonen (50cm). Forvitring vil ifølge MAGIC representere en gjennomsnittlig verdi for 12x12 km ruten, mens forvitring beregnet ved PROFILE representerer ett punkt innen ruten.

Fordi tålegrensen er en sterk funksjon av forvitringen vil PROFILE gi en lavere tålegrense enn MAGIC i de sørøstlige deler av Norge. I områder med tynt jordsmonn, som f.eks. de sørligste deler av Sør-Norge, vil tålegrensen beregnet med MAGIC eller PROFILE gi små forskjeller.

Selv om tålegrensene varierer i de ulike modellene vil differansen mellom tilførsel av svovel og de beregnede tålegrenser være størst i det sørligste Norge. Utfra en dose-respons mekanisme skulle en forvente at skogens sunnhetstilstand i dette området er redusert. En sammenstilling av kronetetthet med jordkjemiske data fra Sør-Norge viser at de områdene man idag kjenner til er sterkt påvirket av sur nedbør, dvs. områder i Agderfylkene og Telemark, har en lavere kronetetthet enn andre områder.

SUMMARY

Maps of critical loads of acidity and exceedance (sulphur) for coniferous forest soils in Norway have been compiled based on the soil survey data of NIJOS and NISK, the atmospheric deposition data of NILU, the forest productivity data of NIJOS, and the surface water chemistry data base of NIVA. Two methods were used: the dynamic MAGIC model and the static PROFILE model. MAGIC results are available for about 200 of the 450 12x12 km grid squares with coniferous forest. Norway has about 2300 grid squares total.

The critical loads for soils were calculated using the criterion that the Ca/Al molar ratio in soil solution should not fall beneath 1.0. The uppermost 50 cm of soil was considered. For MAGIC the scenarios were run 50 years into the future under the assumptions that nitrogen deposition and nitrogen retention are unchanged relative to the present.

The results show that the critical load for soils is higher than the critical load for water (ie., soils are less sensitive). Critical loads calculated by MAGIC are somewhat higher than those calculated by PROFILE for about 30 squares for which sufficient data are available for both methods.

Critical loads for soils are exceeded by present-day sulphur deposition in many squares in southernmost Norway. There are indications that crown density of spruce stands in these squares is also lower than in nearby squares in which the critical load is not exceeded.

Future work with mapping critical loads for soils in Norway might include soils in birch and other vegetation types and evaluation of nitrogen alone and in concert with sulphur deposition.

INTRODUCTION

Acid deposition has damaging effects on forest soils and vegetation, and it is widely accepted that reductions in the emissions of S and N are required. The calculation of critical loads for different receptors, such as surface waters, groundwater and forest soils, is an approach which seeks to link the emission abatement strategy with the capacity of ecosystems to withstand and buffer the effects of acidic deposition. In simple terms, the critical load is defined as: "*A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge*" (Nilsson and Grennfelt 1988). Today, twenty-nine countries have agreed to map critical load of acid deposition by the end of 1991. This mapping will form a basis for further international negotiations on reducing acidifying emissions. The work is coordinated on by the UN-ECE Task Force on Mapping.

Methods for estimating critical loads for forest soils include static models based on soil type or soil mineralogy and dynamic models which take into account the time-dependent processes involved in soil acidification and recovery (Sverdrup et al. 1990). Until now, mapping of critical loads in Europe has mainly been done with static models. The principle of static models is based on a mass balance which states that all sources of acidity should be balanced by all sources of alkalinity in the forest soils. Thus, inclusion of the entire path of change in soil-pH, base saturation, etc., from the original pre-acidification state to the post-acidification state is circumvented, and the final steady state is calculated directly. Fig. 1 illustrates how this balance is formed for forest soils. Sources of acidity are acid deposition and uptake of base cations and ammonium. Sinks of acidity are chemical weathering and nitrate uptake. Leaching of alkalinity or acidity is a product of the chosen chemical criteria. In Nordic forests, the acidification of soils and its effects arise both naturally as a result of soil formation and development (podzolization) and as a result of the input of acid deposition from external sources. Distinguishing external and internal sources of acidity is difficult. Therefore, all sources of acid input are considered, and if sources of alkalinity equal the sources of acidity, there will be no net soil acidification and hence no harmful effects will occur. Thus the essence of calculating the critical load is to find the total acid deposition that makes the balance and by convention the critical load is the forest soil's capacity to neutralize external and internal sources of acidity.

In this report the critical load is calculated by two different methods; a dynamic and a static model. A main difference between these methods is the time aspect. The dynamic model, **MAGIC**, is a catchment model which uses both surface water and soil chemistry to obtain the critical load for forest soil. Thus, MAGIC calculates a critical load which represents a characteristic value for a catchment. A comparative study of critical loads calculated by MAGIC for surface waters and forest soils for 9 catchments in southern Norway shows that surface waters are more sensitive to acid deposition than are forest soils in catchments with thin soils (Wright et al. 1990), whereas in areas with thick soils like Nordmoen, surface waters tolerate a higher load of acid deposition than do forest soils (Wright et al. 1991).

The static model, **PROFILE**, is a multi-layer soil chemistry model reflecting natural stratification of soils (Warfvinge et al. 1992). The calculation of critical load is site specific and only the upper 50 cm of the soil (taken as the rooting zone) is considered. The long-term resistance against acidity is chemical weathering, and thus the critical load calculated by PROFILE is closely related to the chemical weathering rate (Sverdrup et al. 1992).

Processes with time-dependent aspects are not taken into account by static models; only processes that persist over periods of many decades are considered. Temporary effects on N and S cycling, such as cation exchange, adsorption reactions and enhanced N-immobilization by organic matter, are not included. Furthermore, static models cannot predict the time period over which forest growth and/or production is maintained while critical loads are exceeded. Dynamic models include variations in soil chemistry with time. Due to the depletion of the ion-exchange pool with time the calculated critical load will change with time until a long-term static value is reached. Given similar system boundaries and long time (100-200 years) the two different methods should give similar critical loads.

The major aim of this report is to present the approach, and results for mapping the critical load of acidity in coniferous forest soils in Norway using the static and the dynamic models.

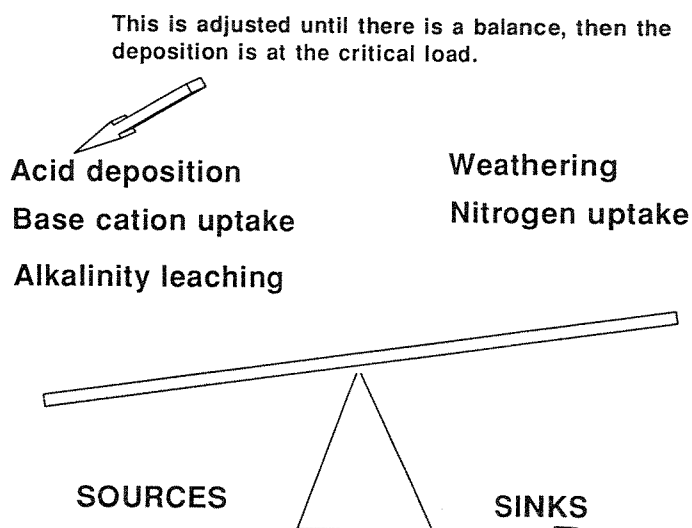


Figure 1. The principles of calculating the critical load using the mass balance method and the dynamic model. In the calculation of the critical load, the sources of acidity are balanced against the sources of alkalinity in the system by adjusting the deposition input of acidity. The acid deposition is represented by the net acidity of the deposition, incorporating both sulphur, nitrogen and base-cation constituents.

1. CRITICAL LOAD CRITERIA AND DEFINITIONS

The calculation of a critical load is dependent upon a critical load criterion which makes it possible to relate the critical value to an effect on trees. Several different chemical criterias are mentioned in the Mapping Manual; Mapping Critical Loads for Europe (Hettelingh et al. 1991), but it has not yet been possible to directly and quantitatively relate any chosen chemical criterion in forest soils to a response to acid deposition. The chemical criterion used in this work is a Ca/Al molar ratio limit of 1 in the soil water. The effect of soil acidification is reflected by using the Ca/Al ratio because a depletion of the ion exchange pool will over the long-term result in a mobilization of aluminium in the soil water. High concentrations of aluminium are toxic to roots and available field and laboratory data indicate that Ca/Al=1 may be used as an indicator for separating declining stands from healthy ones (Ulrich 1983, Schulze 1989, Sverdrup et al. 1992). The estimated critical load is dependent on the choice of Ca/Al ratio, because this threshold is calculated by increasing or reducing the amount of acid deposition until the criteria is fulfilled. There is still a gap of knowledge concerning the effect of low Ca/Al ratios on forest growth, and the calculated critical load for forest soils should be interpreted with care.

2. DATA BASES

2.1. NIJOS SOIL DATA BASE

The calculations of critical loads to forest soils are based on data from the NIJOS forest monitoring plots on a 9 x 9 km grid and on the surface water data base from NIVA and NILU's deposition data on a 12 x 12 km grid. The maps of critical loads are based on a 12 x 12 km grid where all input data is aggregated to this grid net.

The NIJOS soils data are from areas in productive spruce and pine forests (Esser and Nyborg 1992). A soil pit was objectively located within the representative vegetation type five meters from the plot center in the 9 x 9 km grid. The soil pit was dug to at least a 50-cm depth where possible. Soil stratification and soil moisture class were determined in the field.

Soil profile descriptions are based on guidelines described by Sveistrup (1984), with some simplifications. Samples were collected from each horizon, with the exception of thin or discontinuous horizons, and composited by horizon with auger samples collected in the area around the soil pit. Auger samples were taken in the same vegetation type that the profile represented. Composite auger samples were mixed with samples from the soil pit, resulting in one sample for each horizon. In boulder-rich moraine or with strongly indurated pans, most of the sampled material was taken from the soil pit.

Soil samples collected from the monitoring plots were pre-treated and analyzed at the Agricultural Laboratory at JORDFORSK. The samples were dried at 38 °C, crushed and sifted through a 2-mm sieve. All analyses were performed on pre-treated samples.

Exchangeable cations were determined from an extract of 1 M NH_4NO_3 . Concentrations of Ca, Mg, K, and Na in the extract were determined on a Jarrell Ash ICAP-1100.

For the determination of exchangeable acidity, 50 ml of the filtrate from the analysis of exchangeable cations was titrated to pH 7.0 with 0.05 M NaOH.

Particle-size distribution was determined for the B-horizon based on the method described by Elonen (1971). The sample was pre-treated with H_2O_2 and HCl before pipetting for the clay and silt fractions (clay <0.002-mm; fine silt 0.002-0.006-mm; medium silt 0.006-0.02; coarse silt 0.02-0.06-mm diameter) and wet sieving for the sand fractions (fine sand 0.06-0.2-mm; medium sand 0.2-0.6-mm; coarse sand 0.6-2.0-mm diameter).

For all B-horizons, citrate-dithionite soluble Fe and Al (SCS 1972) and pyrophosphate soluble Fe and Al were determined (Bascomb 1968). Results were used to classify the soils.

2.2. FOREST PRODUCTIVITY

The NIJOS coniferous forest monitoring programme includes 623 plots from a 9 x 9 km permanent national grid. The plots are located in *Picea abies* or *Pinus sylvestris* forests. Only plots with particle-size analysis, largely podzols, brunisols and some regosols and gleysols (Agriculture Canada Expert Committee on Soil Survey 1987), are included in this investigation. Plot setup is described in Kvamme (1992). Sampling and registration of the plots occurred from June through August, 1988-1991.

Annual yield was estimated in $\text{ha}/\text{m}^3/\text{yr}$. Yield capacity for a given site quality class and tree species is the maximum mean annual increment for an established stand which has a high density and will be thinned for obtaining near maximum production. The annual yield capacity gives the maximum stem harvest. Actual yield will be lower. We use a scaling factor of 40 % in the western part of Norway to 70 % in the main forest region in southern Norway to get the net annual increment. Values for different classes in the applied site quality system (H_{40}) are published by Tveite & Braastad (1981).

2.3. NIVA WATER DATA BASE

The Norwegian Institute for Water Research (NIVA) has assembled a database for lakewater chemistry for each square in the 12 x 12 km grid. The data come mainly from the 1000 lake survey conducted in 1986 (Henriksen et al. 1988) and supplemented by similar data from other sources as described by Henriksen et al. (1990). The database includes values for concentrations of major ions and specific discharge.

2.4. NILU ATMOSPHERIC DEPOSITION DATA BASE

The Norwegian Institute for Air Research has estimated present-day deposition (wet plus dry) of sulphur and nitrogen compounds to each square in the 12 x 12 km grid. The estimates are based largely on deposition measurements taken in 1985-88 at monitoring stations throughout Norway. Estimated dry-deposition takes into account the type of vegetation cover. Details are given by Henriksen et al. (1990) and Løvblad et al. (1992).

3. MODELS.

3.1. THE MAGIC MODEL

3.1.1. Model description.

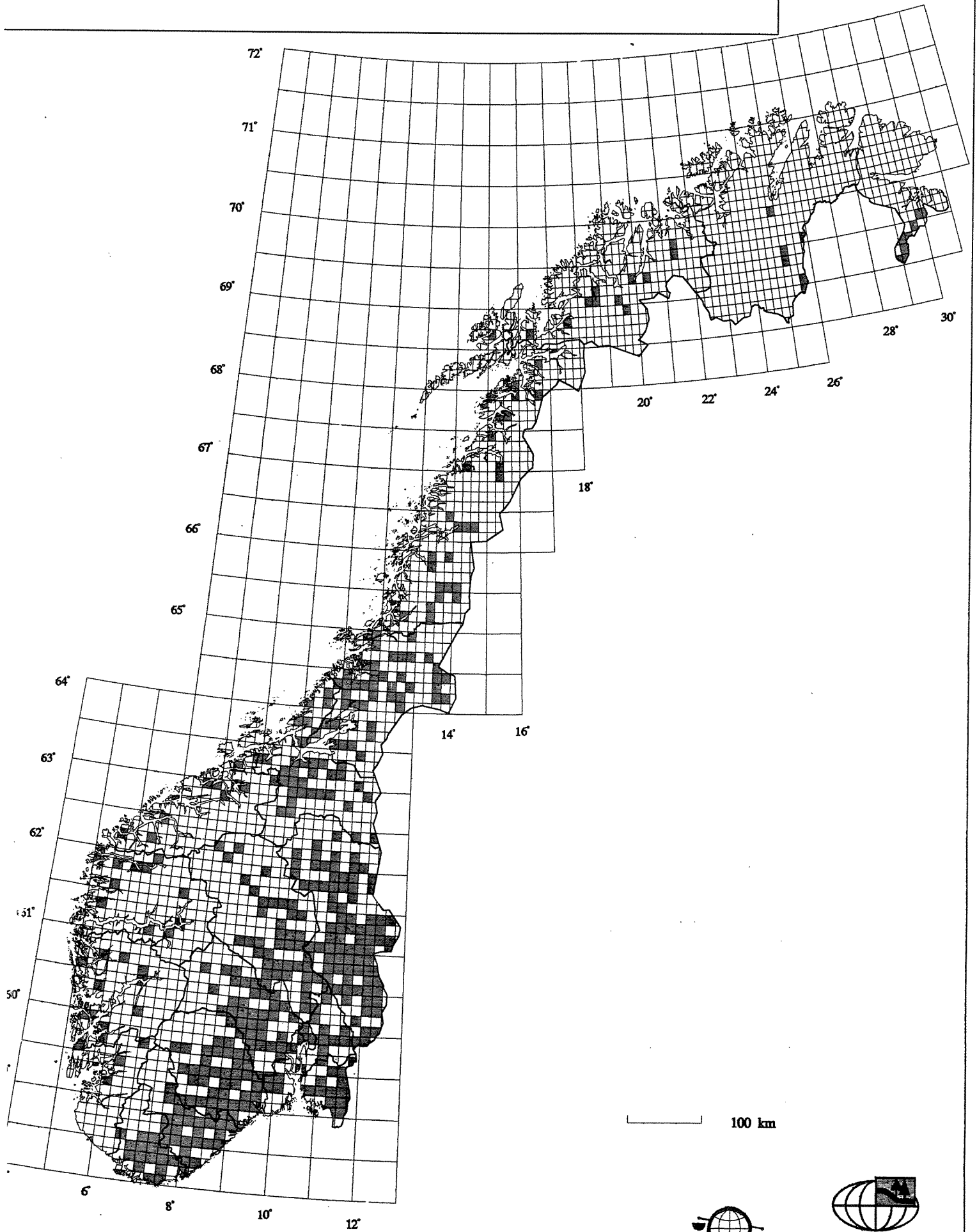
MAGIC (Model for Acidification of Groundwater In Catchments) is an intermediate-complexity process-oriented model for constructing acidification history and predicting future acidification over time periods of decades to centuries (Cosby et al. 1985a, 1985b). MAGIC makes use of lumped parameters on a catchment scale and focuses on chemical changes in the soil caused by atmospheric deposition, vegetation, and leaching to runoff. The processes in MAGIC include atmospheric deposition, sulfate adsorption, cation exchange, CO₂ dissolution, precipitation and dissolution of aluminum, chemical weathering, uptake and release of cations by vegetation, and export in runoff.

MAGIC has been extensively used in a variety of applications at sites in both North America and Europe. Application of MAGIC to the whole-catchment experimental manipulations of the RAIN project shows that this intermediate-complexity lumped model predicts the response of water and soil acidification to large and rapid changes in acid deposition (Wright et al. 1990). These results reinforce other evaluations of MAGIC such as comparison with paleolimnological reconstructions of lake acidification (Jenkins et al. 1990) and changes in regional lake chemistry in southern Norway (Wright, Cosby and Hornberger 1991). In addition several of the assumptions in MAGIC have been tested experimentally (Grieve 1989). MAGIC is one of several dynamic models included in the Mapping Critical Loads (Sverdrup et al. 1990). Together these applications indicate that MAGIC provides a robust tool for predicting future soil and water acidification following changes in acid deposition.

3.1.2. Modelling procedures.

Here we use MAGIC to map critical loads for soils and surface waters in Norway. We use the surface water database from NIVA and the forest soil survey data of NIJOS to derive a data set of paired lake and soil chemistry for each square in the 12 x 12 km grid. There are ca. 2300 such grid squares in Norway, of which about 460 are in spruce or pine forests. (Fig. 2).

Squares with soil data



The NIJOS forest soil data are based on a 9 x 9 km grid, whereas the critical loads maps are based on a 12 x 12 km grid. (Actually, the critical load grid is 0.5° latitude by 1.0° longitude with 16 subdivisions within each. Thus the grid widths decrease at higher latitudes.) The 601 soil profiles from the NIJOS 9 x 9 km grid covered 458 squares of the 12 x 12 km grid. Averages were taken of soil profiles falling within the same grid square. Of these 458 squares, only 327 had complete water chemistry data. MAGIC calibrations of the 327 paired soil and water chemistry data was successful in 217 cases. Of these critical loads could be calculated for 212 squares. These form the basis of the map of critical load (sulphur) for forest soils.

The original soils data were analyzed by horizon. These were aggregated to obtain single values for soils less than 60 cm in depth, and values for 0-50 cm and >50 cm for soils with total depth greater than 60 cm. The aggregation procedure weighted by horizon thickness and bulk density and also corrected for stone and pebble content. The MAGIC calibrations used a 1-box version for soil less than 60 cm depth and a 2-box version for soils greater than 60 cm in depth with upper box 0-50 cm and lower box >50 cm.

Uptake of base cations for each grid square were estimated from values of stem+bark harvest (see 2.2. above) and typical concentrations of nitrogen, calcium, magnesium and potassium in stem and bark (K. Rosen, pers. comm.). The concentrations in stem and bark were taken from different literature sources and typical concentrations in stem and bark are: calcium = 0.15 %, magnesium = 0.09 %, potassium = 0.06 % and $N = 1.12 * (K + Ca + Mg)$.

Present-day deposition of major ions was estimated from the water chemistry and specific discharge under the assumptions that all sulphur and chloride comes from atmospheric deposition, and that the deposition of Na, K, and Mg is of seasalt origin. Deposition of Ca, NO_3 and NH_4 are estimated from ratios of these elements to sulphate in precipitation in Norway.

The MAGIC calibration procedure assumes steady-state conditions 140 years in the past (year 1846); at that time deposition of pollutants is assumed to be negligible and chemical composition of soils and surface waters was not changing. During the ensuing 140-year period to 1986, the deposition of sulphur was assumed to increase parallel to the estimated historical emissions of sulphur in Europe.

We use an automatic calibration routine (Jenkins and Cosby 1989) to obtain estimates of weathering rates and original base saturation in the soil such that when subjected to the 140-year sulphur deposition the simulated water and soil chemistry for the year 1986 agree with the measured values.

The critical load at each grid square is calculated using the MAGIC model under the condition that sulphur deposition is suddenly changed to a new level and then held constant for 50 years. MAGIC is run repeatedly with different levels of deposition until the criterion of Ca/Al molar ratio = 1.0 in soil solution in the upper 0-50 cm (taken as the rooting zone) is met. This deposition is the critical load (sulphur) for soil. For water the criterion of ANC = 20 $\mu\text{eq/l}$ in surface water was used, where

ANC (acid neutralizing capacity) is defined as the difference in sum of equivalents of base cations (Ca, Mg, Na, K) less sum of equivalents of strong acid anions (SO_4 , Cl, NO_3). For all cases it is assumed that the loading and retention of nitrogen compounds are not changed from present-day conditions.

3.2. THE PROFILE MODEL

3.2.1 Model description.

The multi-layer soil chemistry model PROFILE is a soil acidification model which calculates critical loads by a steady-state mass balance approach (Warfvinge et al. 1992). The steady-state mass balance implies that for each soil layer all sources of acidity must be balanced by all sources of alkalinity (Fig. 1). The steady state approach implies certain assumptions:

- Capacity factors in the soil such as cation exchange and mineral abundance is kept constant.
- Only processes such as chemical weathering, precipitation and uptake, etc., that exist over a period of many decades are considered. The input must represent long-term averages.
- The effect of soil acidification rates and seasonal variation of input variables, such as CO_2 -pressure, nitrification rates and soil moisture contents, are not included.

PROFILE has many elements in common with other contemporary soil acidification models, but regarding weathering reactions, PROFILE allows the weathering rate to be calculated explicitly from independent soil properties. For dissolution in the natural soil environment, the rate is controlled by reactions with hydrogen ion, water, carbon dioxide and organic acids. All these reactions are slowed down by aluminum and the base cations released in the reaction. The weathering rate will be the sum of the rate of all these simultaneous reactions (Sverdrup 1990, Warfvinge et al. 1992).

3.2.2. Derivation of input data.

The general input data to PROFILE include precipitation, runoff, temperature and uptake. Data were taken from the national data bases. The most important data from each soil layer is soil moisture classification, soil mineralogy and texture of the C-layer, base cation and nitrogen uptake. Soil moisture was estimated using field evaluated soil moisture class, particle-size distribution and pF-curves. Soil mineralogy in the C-layer is derived semi-quantitatively for 50 sites (Pederstad 1982). Analyses for each site were done on two weight fractions; $> 2.7 \text{ g/cm}^3$ and $< 2.7 \text{ g/cm}^3$. Soil texture and the conversion from a standard sieve curve to surface area was quantified by using a specific surface area for the clay fraction of $8 \text{ m}^2/\text{g}$, for silt $2.2 \text{ m}^2/\text{g}$ and for sand $0.3 \text{ m}^2/\text{g}$.

3.3. EMPIRICAL F-FACTOR MODEL FOR WATER

Henriksen (1980) developed an empirical model for predicting water acidification. This model is based on present-day water and precipitation chemistry and is static in that it specifies the water chemistry resulting from a given change in deposition without specifying the time at which this new water chemistry will exist. The model thus does not provide information as to length of time required to achieve steady-state following change in acid deposition.

The empirical model is one of the static models included in the Mapping Critical Loads (Sverdrup et al. 1990) and is currently being used in conjunction with mapping critical loads for freshwaters in Norway (Henriksen et al. 1990) and the other Nordic countries (Henriksen et al. 1992).

4. RESULTS

4.1. MAGIC

The map of critical loads (sulphur) for forest soils in Norway reveals very low levels in southernmost and southeastern Norway with higher levels in central and northern Norway (Fig. 3). This general picture reflects the distribution of granitic bedrock (and hence moraine generally derived from granitic bedrock) in Norway. Soils derived from these materials typically have very low rates of chemical weathering. Critical loads will be low in such soils.

Critical load (sulphur) for forest soils is exceeded in southernmost Norway and in several areas of eastern Norway (Fig. 4). Southernmost Norway is generally highly sensitive and receives high loadings (for Norway) of acidic pollutants.

The results for 212 grid squares indicate that the critical load for soils is generally about 2X higher than the critical load for water (Fig. 5). For areas with thin soils, the soil criterion is less stringent than the water criterion. If the water is protected, then the soils will also be protected. This result agrees with earlier MAGIC applications to calibrated catchments in Norway (Wright et al. 1990).

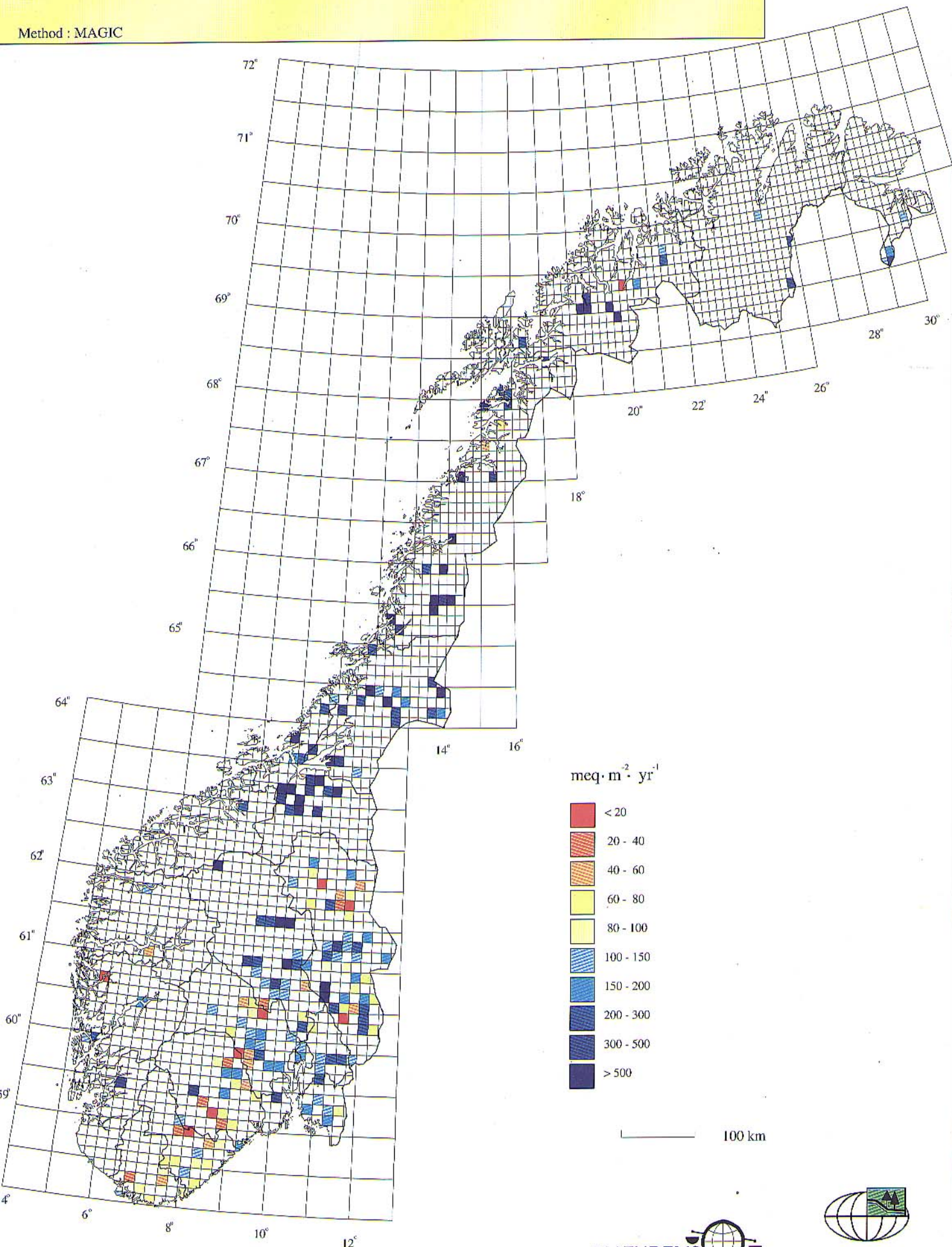
The critical load for water obtained by the dynamic MAGIC model roughly agrees with the critical load derived by the static empirical method (Fig. 6). This implies that for surface water the simple empirical method may be sufficient for setting critical loads. Again, this result agrees with previous applications of MAGIC to calibrated catchments in Norway (Wright et al. 1990).

4.2. PROFILE

The map of critical loads calculated by PROFILE indicates lowest values in southeastern Norway (Fig. 7). The capacity for long-term resistance to soil acidification due to acid deposition is mainly determined by the cation supply from chemical weathering. Since weathering is the major factor replenishing the pool of

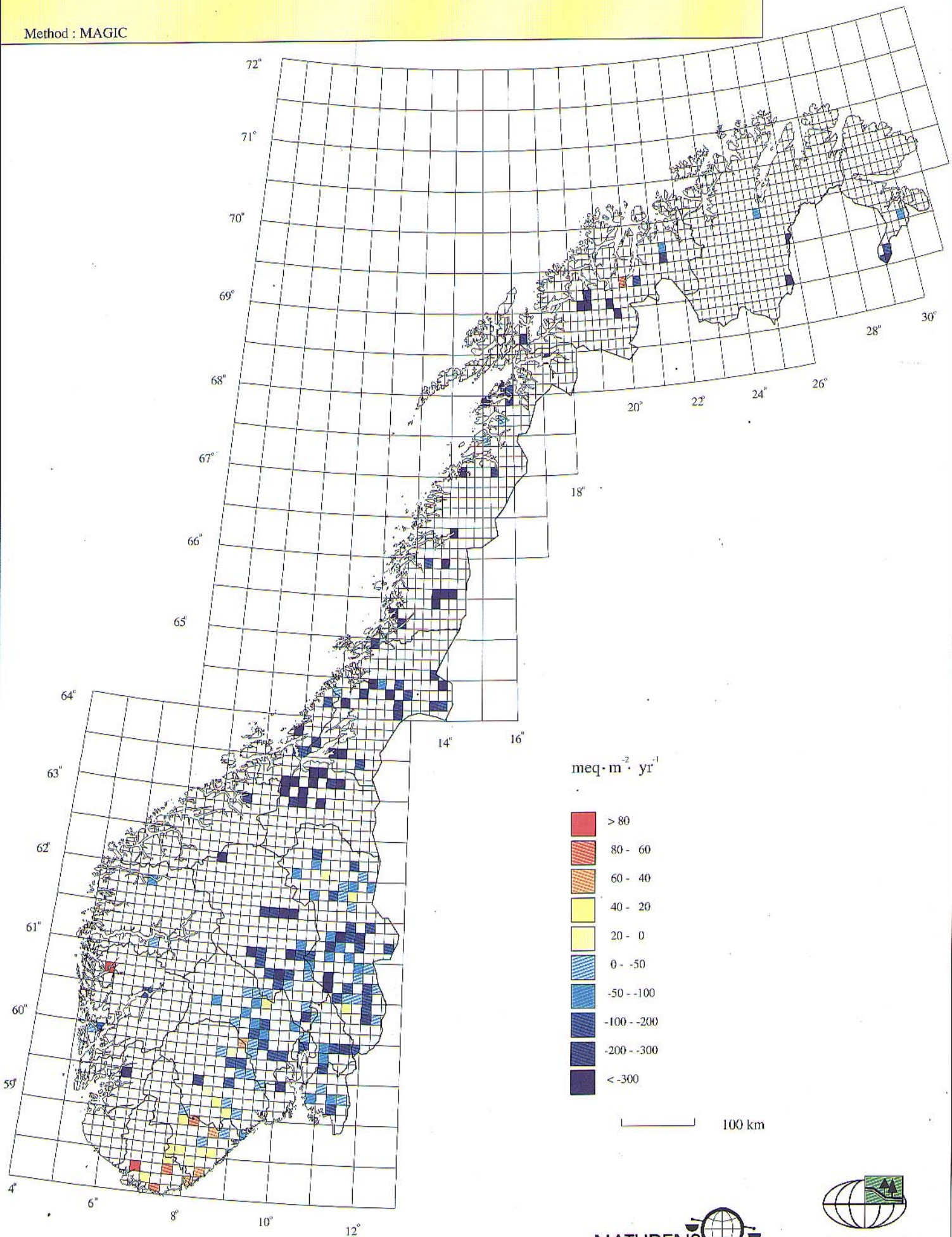
Critical Load - forest soil

Method : MAGIC



Exceedance of the Critical Load - forest soil

Method : MAGIC



Critical loads

SO₄ meq/m²/yr

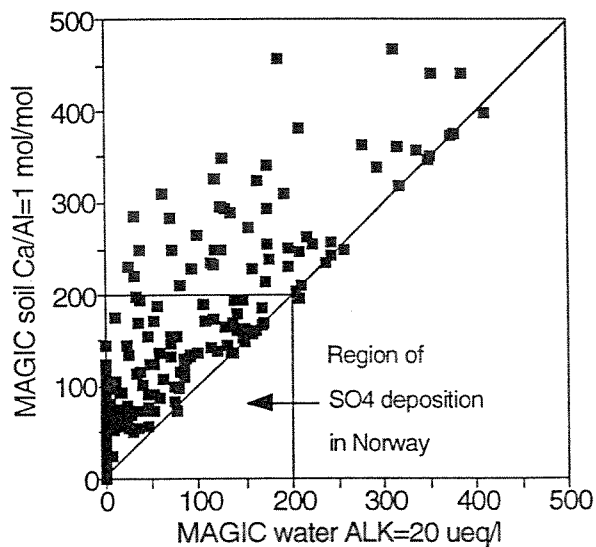


Figure 5. Critical load for soil vs. critical load for water at 212 grid squares in Norway as calculated by MAGIC. For soil the criterion is Ca/Al molar ratio of 1 in soil solution in the upper 50 cm soil. For water the criterion is ANC 20 $\mu\text{eq/l}$. The box indicates range of present-day SO₄ deposition in Norway.

Critical loads

SO₄ meq/m²/yr

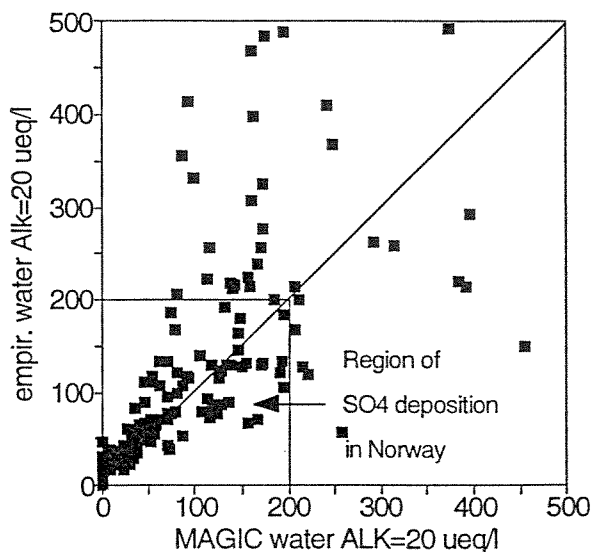
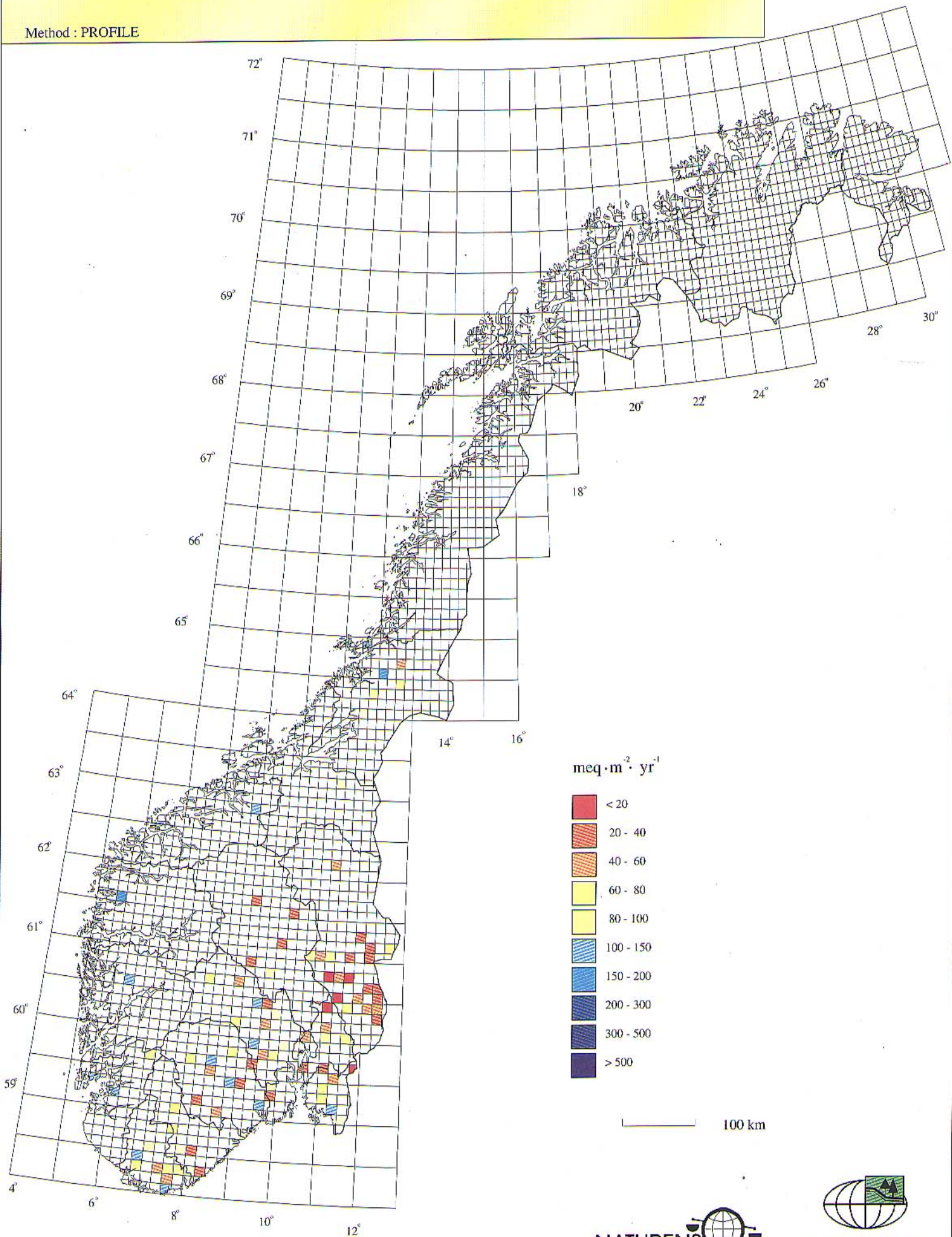


Figure 6. Critical load for water as calculated by MAGIC vs. critical load for water as calculated by the empirical model.

Critical Load - forest soil

Method : PROFILE



exchangeable base cations, the rate of weathering primarily determines the critical load of acid deposition. The variations of critical loads to forest soils are positively correlated with the variations in the chemical weathering rate ($r^2 = 0.31, p < 0.01, n = 92$). Southeastern Norway has an underlying bedrock (the sparagmite region) dominated by resistant minerals such as quartz and albite. This results in low weathering rates and low critical loads. The higher weathering rates and critical loads in southernmost Norway are explained by a more humid and temperate climate in this area. Subtracting the critical loads from the present deposition of sulphur gives a high exceedance of critical loads in the southernmost area. PROFILE calculations have been done on 92 points in southern Norway. According to these calculations, in the long term, 60 % of the forest grid points cannot withstand the sustained present deposition of sulphur without suffering forest damage.

5. DISCUSSION

5.1 A COMPARISON OF MAGIC AND PROFILE

5.1.1 Dynamic vs Static Models.

MAGIC and PROFILE critical load calculations are available for about 30 grid squares. These are located throughout southern Norway. There is no apparent relationship between these values; both methods give critical loads in the general range of 0-200 meq/m²/yr, but at any given grid square the values differ substantially (Fig.8).

Most of the points have somewhat higher CL as calculated by MAGIC relative to PROFILE. This is perhaps due to the fact that MAGIC takes into account the base cation pool in the soil which must first be depleted before the Ca/Al ratio in soil solution will begin to decrease significantly. If MAGIC is allowed to run for 140 years, the CL values decrease somewhat (Fig.9).

The system tolerates less acid deposition if it continues over more years. Under this long-term scenario the values from PROFILE and MAGIC are comparable for most points, although there are still several grid squares for which the two methods give greatly differing results. The difference between the two methods is mainly due to different chemical weathering rates used. Although the difference in critical load is best explained by chemical weathering rates, the model principle with multi layer and one layer soils will in general give different critical loads (Warfvinge et al. 1992b). PROFILE tends to give lower critical loads than MAGIC.

5.1.2. Spatial Considerations.

Some of the discrepancy between MAGIC and PROFILE CL calculations may be explained by the differences in spatial scales addressed by the 2 methods. For MAGIC, soil data from one or more points within each 12 x 12 km grid square are coupled with water chemistry from one or more lakes within that grid square. Thus, whereas the soil may reflect the conditions within only a few meters around a

Critical loads

Profile v.s. Magic (50 years)

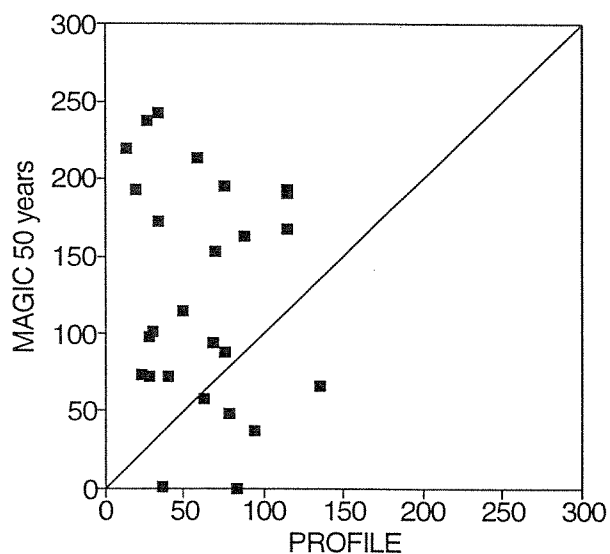


Figure 8. Critical load for forest soils at 30 grid squares in southern Norway as calculated by the steady-state PROFILE model and the dynamic MAGIC model. The MAGIC calculations are made under the condition that the criterion is met within 50 years of constant deposition.

Critical loads

Profile v.s. Magic (140 years)

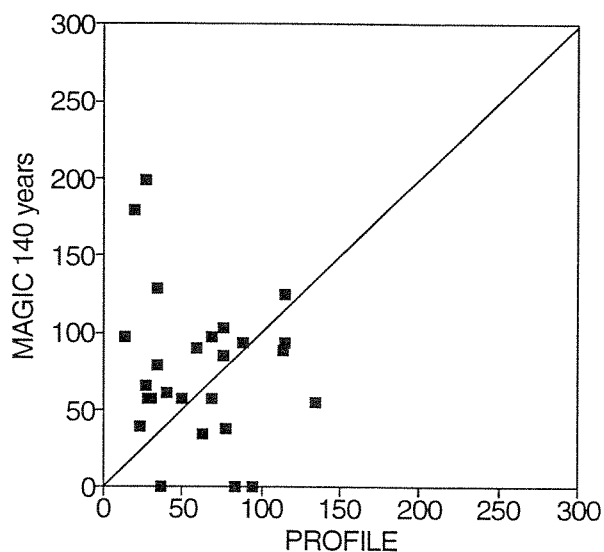


Figure 9. Critical load for forest soils at 30 grid squares in southern Norway as calculated by the steady-state PROFILE model and the dynamic MAGIC model. The MAGIC calculations are made under the condition that the criterion is met within 140 years of constant deposition.

particular point, the water integrates the combined effects of processes occurring over several km². MAGIC uses the water chemistry to place restraints on weathering rates. PROFILE, on the other hand, considers only the soil data. CL values obtained by PROFILE hold only for a particular soil pit, and, due to spatial heterogeneity present in all soils, these values may not be characteristic for larger areas.

Although both methods may give "correct" values, the values when extrapolated up to 12 x 12 km grid squares, may differ substantially. For example, if the soil sampled happens to come from a patch of well-buffered soil with easily-weatherable minerals, but the lake catchment is dominated by silicious parent materials and soils poor in easily-weathered minerals, PROFILE will give a high critical load, whereas MAGIC will give a low critical load. The value obtained by PROFILE holds for that particular soil sample, but the value obtained by MAGIC may be more characteristic for the square as a whole.

5.1.3. Weathering.

The difference in the predictions are consequences of the way chemical weathering is modelled. PROFILE calculates weathering at each specific location and for a stratified soil. MAGIC aggregates soil data and lake data for a 12x12 km square, where the calculated weathering rates are both related to the current status of the soil and the lake. In areas where the thickness of the soil is greater than 50 cm, MAGIC will also consider the alkalinity produced by weathering below the rooting zone. This explains why critical loads are different for southeastern Norway. This area often has thick soils and lakes with a high alkalinity. MAGIC gives an average weathering for the 12x12 km square, and because chemistry of the lakes is more closely related to the deeper soil horizons than to the more sensitive upper horizons, MAGIC calculates a higher critical load and weathering than PROFILE. However, in the southernmost area the soils are thin and patchy with an average soil depth less than 50 cm. Here the calculated critical loads with MAGIC and PROFILE are in the same range. In other words, the system boundaries used by MAGIC and PROFILE are comparable, and in this case the time dependence of critical load by using an infinite time period as done by PROFILE or by using 50 years as done by MAGIC gives approximately similar values (Warfvinge et al. 1992b).

5.2 SCALING UP

The procedure outlined above for calculating critical loads on a 12x12 km grid may not use all available data in some regions of the country. For instance, in southern Norway there have been a number of lake surveys resulting in multiple water samples within many of the 12x12 km grid squares. This additional data permits a comparison of the results of the mapping exercise with a parallel but independent procedure for estimating critical loads based on all available data. This comparison was performed for that region of southern Norway defined as the Birkenes Grid in the EMEP model of atmospheric transport in Europe (Løvblad et al. 1992).

The Birkenes EMEP grid is 150x150 km and contains approximately 150 of the

12x12 grids used to map critical loads in this project. Of these 150 grids, there are 21 that have critical loads calculated (most grids that have no calculated critical loads have no forest). There are, on the other hand, samples of 310 lakes and 84 soils that can be used to calculate a distribution of critical loads for the Birkenes grid as a whole. The distribution of critical loads from the 21 mapped grids can be compared to this larger distribution to evaluate the robustness of the mapping procedure (Fig. 10).

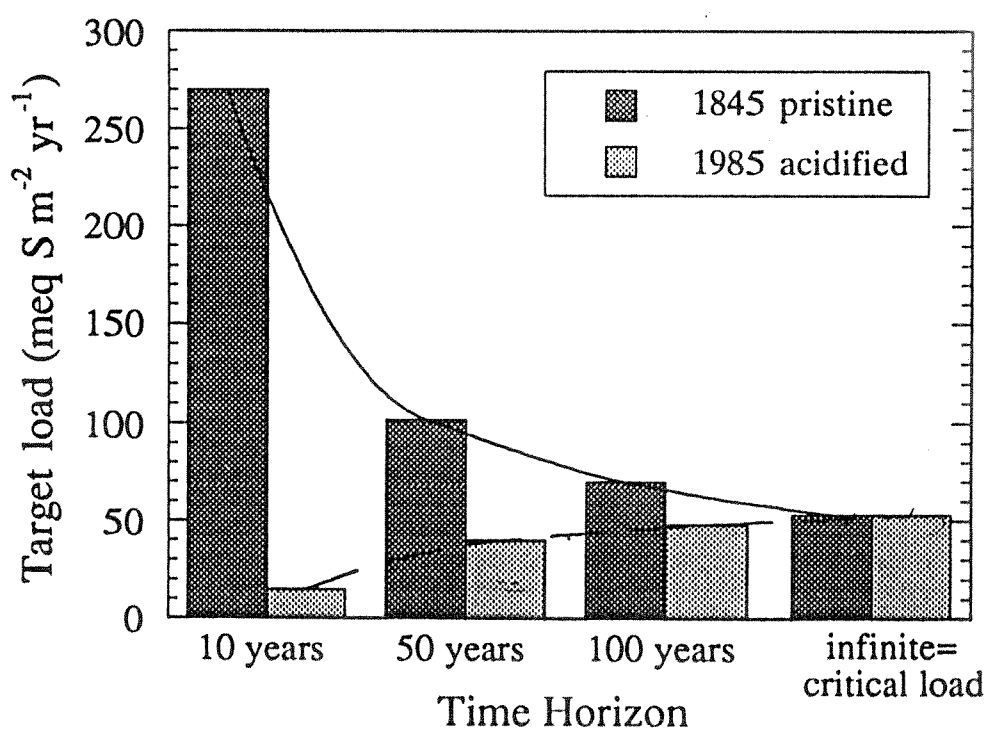


Figure 10. Illustration of the time-dependence of critical load. MAGIC is applied to data from the Birkenes catchment in southernmost Norway. The figure shows the sulphur loading tolerated for 10, 50 and 100 years after which the stream meets the chemical criterion of ANC=0, starting from two different initial states; pristine conditions in 1845 and acidified conditions in 1985 (from Warfvinge et al. 1992).

The estimation of the distribution of critical loads for the Birkenes grid was based on a regional calibration of MAGIC for the lake and soil data in the area. Regional calibrations of MAGIC have been done for larger areas of Norway (Hornberger et al., 1989, Wright et al. 1991) and the procedure used here is similar with a few exceptions, the most important being that estimates of forest uptake of base cations were included in the present regional calibration. Following calibration, the regional model was used to predict distributions of critical loads for ANC = 20, ANC = 0, and Ca/Al = 1 (as described above for the 12x12 km grids).

The distributions of critical loads estimated using all available data in the 150 km x 150 km Birkenes grid compare very well with the distributions based on the 20 mapped 12 x 12 km grids (Figs. 11 and 12). There is especially good agreement between the two distributions for the soil criterion of Ca/Al = 1 and for the lake criterion of ANC = 20 µeq/l. The regional method indicates a slightly lower distribution of critical loads for the criterion ANC = 0 but the differences are not large (especially given that one distribution is based only on 21 samples).

The differences that do occur are consistent with the explanation that the regional method was applied to all systems in the Birkenes grid while the map method was applied only to forested systems. Non-forested areas may be expected to have shallower, less developed soils and thus would be expected to have lower critical loads.

5.3. CONSEQUENCES FOR FOREST VITALITY

The calculated critical loads show that in many areas the supply of nutrients by chemical weathering and precipitation is not sufficient to compensate for the nutrient loss as a result of acid deposition and net nutrient uptake in trees. Southernmost Norway is particularly sensitive to acidic deposition due to a high occurrence of acid gneiss and granite underlying a thin and a patchy soil. The acid deposition in each grid square minus the critical load equals the amount of acid deposition by which the critical loads for forest soils are exceeded. Exceedance implies that the forest ecosystem is in a nutritional imbalance. Within a dose-response framework it follows that the amount of forest damage is related to the sensitivity of the ecosystem and is proportional to the exceedance of the critical load for forest soils. By a grouping of critical load and exceedance as estimated by MAGIC in deciles, Nelleman and Frogner (in prep.) found a concurrence between critical loads and crown density ($r^2 = 0.46$, $p < 0.05$, $n = 10$). Forest damage in terms of crown density was correlated to the exceedance of the critical loads ($r^2 = 0.69$, $p < 0.05$, $n = 10$).

5.4. NITROGEN

The critical load map for Norwegian coniferous forest soils is constructed under the assumption that nitrogen deposition and nitrogen retention both stay constant in the future. If nitrogen deposition increases or if leaching of nitrate increases (or both) then the soils will tolerate less sulphur deposition. Critical loads for sulphur will thus be lower.

Critical loads

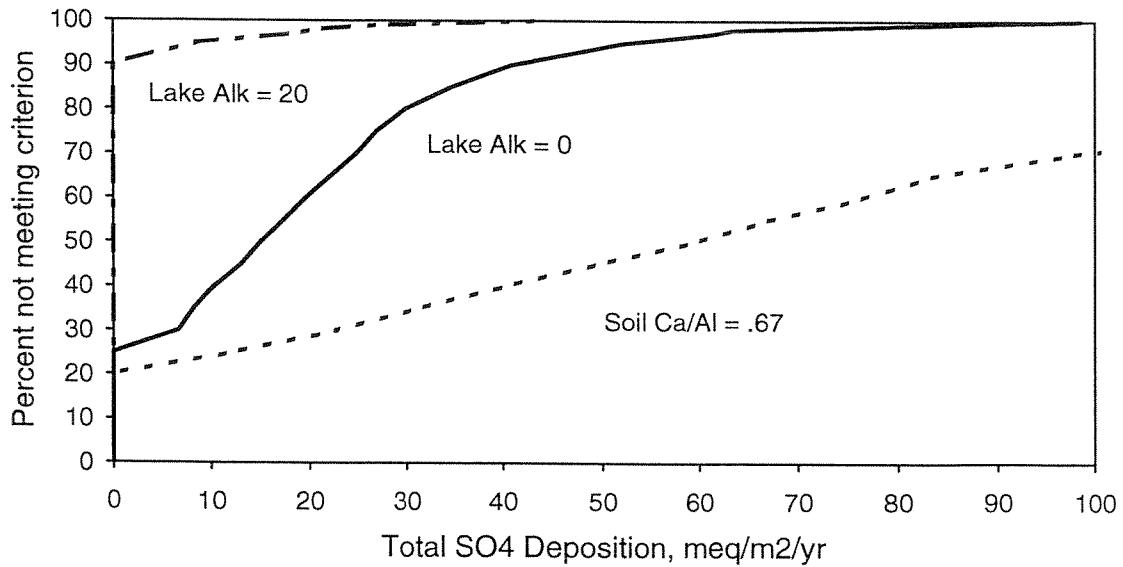


Figure 11. Cumulative frequency of sites not meeting critical load criterion against sulphur deposition as calculated for all lakes and soil plots within the Birkenes square of the EMEP grid (150 x 150 km).

Critical loads

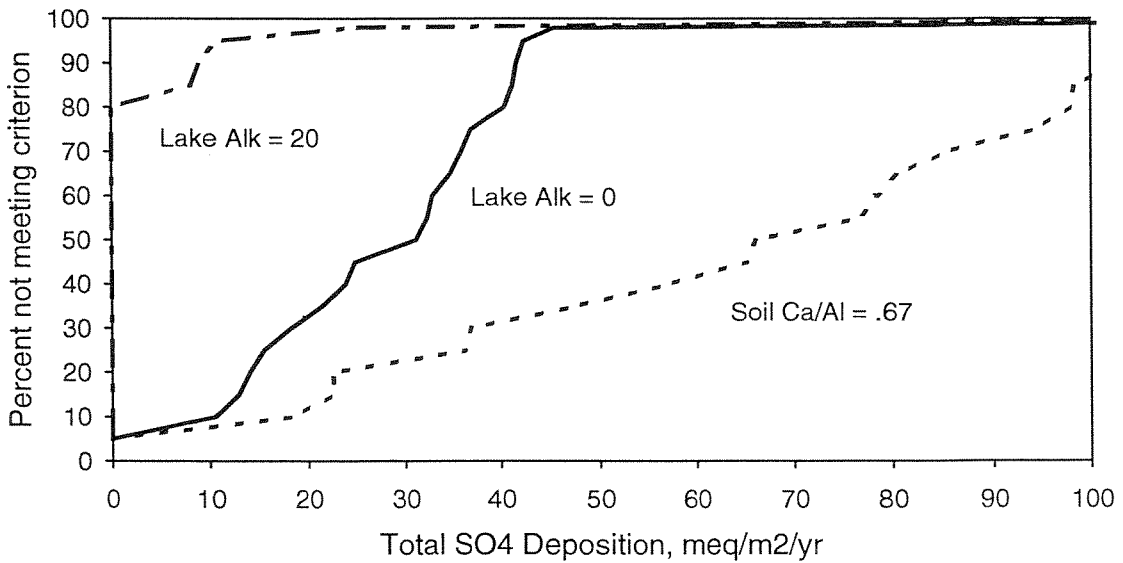


Figure 12. Cumulative frequency of sites not meeting critical load criterion against sulphur deposition as calculated for the 20 12 x 12 km grid squares within the Birkenes square of the EMEP grid (150 x 150 km).

Although nitrogen deposition has not increased significantly in Norway during the past 15 years, there is evidence that nitrate concentrations in surface waters in the acidified regions of southernmost Norway are increasing (Henriksen et al. 1988). The catchments are retaining less of the incoming nitrogen. Nitrate, like sulfate, is a strong acid anion and, when leached from acid soil, will be accompanied in part by H^+ and inorganic Al, thereby increasing soil acidification and increasing toxicity of surface waters to fish and other aquatic organisms.

It is difficult to predict whether this trend will continue in the future. Such a prediction predicates a fuller understanding of the phenomenon of "nitrogen saturation". This is the focus of several large research projects currently underway in Scandinavia and elsewhere in Europe, such as "Nitrogen from mountains to fjord" (Henriksen et al. in press), and the NITREX project (Dise and Wright 1992).

In the meantime maps of critical loads for nitrogen and combined sulphur + nitrogen can be constructed for various "best" and "worst" case scenarios using the MAGIC calibrations to each grid square. Each of the scenarios must specify future trends in 2 of the 3 factors (sulphur deposition, nitrogen deposition, and nitrogen retention) to calculate the third. Empirical data for nitrogen retention can be used to place upper and lower limits.

5.5 TARGET LOADS

This set of MAGIC calibrations to each of the grid squares can be used to examine the consequences over space and time of any given future scenario of sulphur deposition. Thus maps can be constructed showing exceedance of critical loads at 10-year intervals into the future given a 30% reduction in sulphur deposition over the period 1993-2006. Or one can calculate the reduction in deposition necessary to reduce the exceedance by one half (close the gap between deposition and critical load by 50%) at all grid squares where exceedance is currently greater than zero. Thus the set of calibrations provides a management tool available for the setting of target loads.

5.6 FUTURE WORK

Work with constructing maps for critical and target loads for soils in Norway can continue along several lines:

- a. Estimate critical loads for the remaining grid squares in coniferous forest for which there are soils data but either incomplete water chemistry data or unsuccessful MAGIC calibrations. The total number of squares with CL estimates can probably be increased from 212 at present to about 350 of the possible 458 squares with soils data.
- b. Continued comparison of MAGIC and PROFILE methods for estimating critical loads for soils.

- c. Expansion to areas with other vegetation types such as birch forest. NIJOS is currently conducting a survey of birch forests in Norway, and the soil data can be used to calculate critical loads using MAGIC in the same manner as for coniferous forest soils.
- d. Maps of critical loads for nitrogen, and combined nitrogen and sulphur maps. The set of calibrated MAGIC files for each of the 212 grid squares can be used to calculate critical loads given assumptions about future retention of nitrogen, and future deposition of nitrogen and sulphur.
- e. Mixed water and soil maps. A combined map showing critical load for the more sensitive receptor (water or soil) at each grid square can be constructed.

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