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Critical loads for soils in Norway

Preliminary assessment based on data from 9 calibrated catchments

Norwegian Institute for Water Research NIVA

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Abstract:

Critical loads for acid deposition with respect to soils are calculated for 9 calibrated catchments in southern Norway. Two methods recommended by the UN-ECE Handbook on Mapping Critical Loads were used: the static empirical model, and the dynamic MAGIC model. The critical load for soils follows two criteria: runoff water must have alkalinity > 0 (fish criterion), and the Al/Ca equivalent ratio in soil solution < 1.5 (forest criterion). The results show that for these Norwegian sites with thin and patchy soils, the fish criterion is always the more stringent. Further work should evaluate regional soils data and assess the future role of nitrogen.

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1. Tålegrenser
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Critical loads for soils in Norway

Preliminary assessment based on data from 9 calibrated catchments

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SAMMENDRAG

Tålegrenser for jord er av interesse fordi endringer som skjer i jorda påvirker biologiske organismer i det terrestriske økosystemet som f.eks. trær. Men jorda virker også inn på det vannet som går igjennom mediet og når vann og vassdrag.

Tålegrensen for jord har blitt definert som den høyeste belastning av forsurende komponenter som ikke vil gi skadelige effekter på økosystemenes struktur og funksjon. Hvis målet er å beskytte jorda over svært lang tid (> 1000 år), vil tålegrensen nærme seg null. En mer praktisk grense er å si at forsurende komponenter ikke skal føre til uakseptable endringer i jorda i løpet av en periode på 50-100 år.

Kriteriene for "uakseptable endringer" må sees i forhold til effekter på terrestriske og akvatiske organismer. En rekke slike kriterier er satt opp. Av kriterier som kommer inn både når det gjelder jord og vann, er pH, alkalinitet, aluminium og forholdet Ca/Al. Når vi omtaler jord i denne forbindelse, mener vi i hovedsak skogsjord. Dyrket jord har liten interesse på grunn av de dyrkningsmessige inngrep.

Hensikten med å bestemme tålegrenser er for å sette mål for framtidig deposisjon av forsurende komponenter. Det kan bestemmes separate tålegrenser for skog, jord og vann. En tålegrense for jord er ikke interessant i seg selv, men den kan ses i forhold til skog og vann. Tålegrensen for skog kan være både høyere og lavere enn tålegrensen for vann. Når målet er å beskytte hele miljøet, vil det være den laveste tålegrensen som blir den bestemmende.

I forprosjektet for å bestemme tålegrenser for jord i Norge er det lagt vekt på jordforsuringen. Det er så langt ikke forutsatt noen endringer på grunn av nitrogen. Et hovedproblem når en skal se på endringer i jord, er den store variabiliteten. Mens det i vann vil være en relativt stor homogenitet, så er det det motsatte som preger jorda. Jordegenskapene kan endres radikalt innenfor en

avstand på noen få meter. Som en følge av dette, er ofte kvannkvaliteten bedre kartlagt en jordegenskapene.

For å utnytte kjennskapen til vannkvaliteten i et forsøk på å bestemme tålegrensen for jordforsuring, ble data fra hele nedbørsfelt benyttet. Fordi jordforsuringen påvirkes av flere samspillende prosesser med reaksjonstider på år og tiår, er det behov for å benytte matematiske modeller. Tålegrensene ble derfor estimert ved hjelp av MAGIC-modellen og det ble benyttet kriterier for både skogsjord og vann. Modellen benytter et sett med jorddata fra hele nedbørfeltet og det sier seg selv at det ikke alltid er like lett å anslå ut fra et begrenset antall målinger. Ved bruk av både vann-og jorddata fra samme felt vil modellen sørge for at disse passer hverandre. Beregningene ble supplert ved bruk av en empirisk vannmodell.

Tålegrenser er bestemt i tre typer av felt. Fire små nedbørfelt (Birkenes, Storgama, Langtjern, Kårvatn) med størrelse fra 0.4 til 25 km^2 er undersøkt i tillegg til tre større felt (Vikedal, Gaular, Naustdal) som varierer i størrelse fra 120 til 670 km^2. De to ubehandlete feltene innen RAIN-prosjektet (Risdalsheia og Sogndal) er også inkludert.

De kriteriene som er lagt inn ved beregningene er for vann at alkaliniteten skal være større enn null. Som kriterie for skogsjord er det satt at det ekvivalente forholdet Ca/Al skal være større enn 1.5. Det er også gitt en rekke andre kriterier som også kan beregnes ved bruk av MAGIC. For de 9 feltene som er behandlet her er disse mindre stringente enn de valgte. En må imidlertid være klar over at det er de valgte kriteriene som bestemmer verdien av tålegrensene.

Ellers er de metoder som er benyttet som følger:

* Sammenslåtte jorddata fra nedbørfeltene.
* Nedbør- og avrenningsdata fra SFT-rapporter.
* Kalibrering og optimalisering av MAGIC-modellen for hvert felt.
* Prediksjon av jord- og vannkjemien for de neste 50 år ved forskjellige

svovelbelastninger for å bestemme tålegrensen.

* Prosentvis igjenholdelse av nitrogen er holdt på 1988-nivå.

Følgende tålegrenser for ikke-marint svovel i milliekvivalenter per m^2 og år ble beregnet for vann (fisk) og jord (skog) ved bruk av MAGIC-modellen og for vann (fisk) ved bruk av den empirsike modellen:

	Vann (fisk)		Jord (skog)	Dagens
	MAGIC	Empirisk	MAGIC	nedfall
Birkenes	41	52	153	146
Storgama	21	25	76	69
Langtjern	29	49	80	44
Kårvatn	64	57	125	15
Vikedal	15	32	100	77
Gaular	28	27	120	28
Naustdal	85	62	190	50
Risdalsheia	7	-10	60	101
Sogndal	27	21	74	17

Det kan trekkes flere konklusjoner fra de beregninger som nå er utført:

1. I områder med tynnt jorddekke er tålegrensen for jord bestemt ut fra vannkriteriet om at alkaliniteten skal være større enn null betydelig lavere enn bestemt ut fra skogkriteriet om at forholdet Al/Ca på ekvivalentbasis i jordvæsken ikke må overskride 1.5.

2. Med unntak for Kårvatn, Gaular, Naustdal og Sogndal er tålegrensen for vann (fisk) overskredet med dagens belasning etter begge beregningsmetoder. Tålegrensen for jord (skog) er overskredet bare på Risdalsheia med dagens belastning.

3. Tålegrensene har en tidsavhengig side på grunn av jordforsuringen. Etter som jorda forsures på grunn av surt nedfall vil tålegrensene avta. Det motsatte vil skje hvis jorda blir mindre sur på grunn av redusert surt nedfall. Slike endringer vil ta tiår og kan bare bestemmes ved hjelp av dynamiske modeller.

4. For tidsperioder på mer enn 30 år er tålegrensene beregnet ved bruk av den dynamiske MAGIC-modellen og den empiriske modellen tilnærmet like når kriteriet om vannalkaliniteten settes større enn null.

5. For samtlige felt er tålegrensen for vann lavere enn for skogsjord. Det vil følgelig bli tålegrensen for vann som blir den bestemmende. Dette vil nok være tilfelle de fleste steder i Norge. Også kriteriene for vann er sikrere enn de for skogsjord. Dette gjelder spesielt i forholdet til hvordan disse kriteriene er relatert til fisk og skog. Men når en har beregningsverktøyet, kan det lett korrigeres for endringer i kriteriene.

6. I det videre arbeidet bør områder med dyp jord vurderes. Videre bør ulik nitrogenbelastning inkluderes.

Preface

The work reported in this report was conducted in 1989-90 as a joint project between the Norwegian Institute for Water Research (NIVA) and the Norwegian Forest Research Institute (NISK) under contract from the Norwegian Directorate for Nature Management (DN). It forms part of a comprehensive analysis of critical loads for terrestrial and aquatic ecosystems in Norway being conducted by the Norwegian Ministry of Environment (MD), the Norwegian State Pollution Control Authority (SFT), and the Norwegian Directorate for Nature Management (DN). The Norwegian work is in turn an integral part of critical load mapping now underway under the auspices of the Nordic Council of Ministers (NMR) and the United Nations Economic Council for Europe (ECE).

Richard F. Wright at NIVA was project coordinator and responsible for precipitation and water chemistry data. Arne O. Stuanes at NISK was responsible for soils data for most of the sites. John O. Reuss carried out statistical analysis of the soils data. Mai-Brit Flaten at NIVA conducted the computer simulations using the MAGIC model.

This report is based on soils, precipitation and water chemistry data collected independently as part of SFT's National Environmental Monitoring Programme and the RAIN-project. We thank SFT, NIVA, NILU, NISK, and the RAIN project for use of unpublished data. Our work has profited from helpful discussions with B.J. Cosby and A. Henriksen.

1. Introduction

Deposition of acidic compounds from the atmosphere (acid deposition) leads to acidification of soils and waters (Reuss et al. 1987). Soil acidification is commonly defined as a reduction in the acid neutralizing capacity (ANC) of the soil. An important part of soil ANC is the pool of exchangeable base cations (Ca, Mg, Na, K), usually expressed as soil base saturation.

A number of natural and anthropogenic processes can contribute to soil acidification (Nilsson and Grennfelt 1988). These include:

- increased deposition of acidic compounds
- decreased deposition of basic compounds
- increased primary production and removal of biomass (forestry)
- increased nitrification and oxidation of reduced sulfur compounds

Land-use practice such as afforestation and clearcutting can lead to soil acidification by means of one or more of the above process.

Critical load for soil is of interest because soil acidification affects biological organisms in terrestrial ecosystems (for example, trees) and in aquatic ecosystems (for example, fish). Negative effects in forest ecosystems include shortage of mineral nutrients, nutrient imbalance, and high concentrations of toxic aluminum compounds in soil solution (Nilsson and Grennfelt 1988).

The critical load for soils has been defined as "the highest deposition of acidifying compounds that will not cause chemical changes in soil leading to long-term harmful effects on ecosystem structure and function" (Nilsson and Grennfelt 1988). If the goal is to protect soils over very long time periods (>1000yr) then the critical load approaches zero. A more practical limit is such that acid deposition shall not lead to unacceptable soil acidification over 50-100 years (Nilsson and Grennfelt 1988).

Criteria for "unacceptable change" are set in relation to effects on terrestrial and aquatic organisms. By itself soil is inanimate and the term "damaged" soil has no meaning. With respect to damage to terrestrial vegetation commonly used criteria include the concentration of inorganic aluminum in soil solution and the ionic ratio of aluminum to calcium in soil solution (de Vries 1988, Sverdrup et al. 1989), where the soil solution in rooting depth (0-50 cm) is of primary interest. With respect to aquatic organisms commonly used criteria are that the alkalinity of runoff water should have positive alkalinity and concentration of labile inorganic aluminum less than 50 $\mu g/l$ (Nilsson and Grennfelt 1988, Henriksen and Brakke 1988a).

The purpose of determining critical loads is to set goals for future deposition rate of acidifying compounds such that the environment is protected. Critical loads are determined separately for forests, soils, and surface waters and will differ between these three categories for a given area as well from site-to-site depending upon the inherent sensitivity of the natural environment. The critical load for soils is effectively defined with respect to both waters and forests. In practice, then, at a given site the critical load for forests may be greater or lower than the critical load for water. Because the goal is to protect the whole environment the target load thus becomes the lesser of these critical loads.

In other words if the waters are inherently more sensitive than the forests, the critical load for waters will be lower than that for forests and for the environment as a whole the critical load thus becomes the critical load for waters.

For forests only the soil down through the rooting zone is of interest (for coniferous forests commonly 0-50 cm). Here the critical load for forests may be lower than the critical load for waters because runoff derives from the entire soil column including the commonly more alkaline deeper soil water.

The relative critical loads for forests versus waters can be roughly estimated from the geographical extent of present-day negative effects. In Norway adverse effects to fisheries are widespread in southern Norway (Henriksen et al. 1988, 1989) whereas forest damage due to acid deposition is apparently minor. Thus for Norway it appears that the critical load for waters (and soils under the water criteria) has been exceeded over large geographical areas whereas the deposition lies below the critical load for forests.

In central Europe, on the other hand, the reverse is often the case. In BRD, for example, recent forest damage has been reported, whereas surface water acidification is much less common. This is probably because the soils in central Europe are generally thicker such that whereas soil acidification has affected the forest status, the surface waters derive from runoff that has been in contact with the deeper more alkaline soil horizons. Thus in many areas of the BRD the critical load for forests (and soils under the soil solution criteria) has been exceeded whereas deposition lies below the critical load for surface waters.

The situation is not this simple, however, because of the time lags involved. The adverse effects of a given loading of acid deposition may not be manifest for many years or decades after the onset of acid deposition. For example, the present-day forest damage in BRD was not apparent only 10 years ago, although loading of acid deposition has not changed appreciably over the past 20 years. Similarly changes in surface water chemistry lag behind changes in deposition and fish population status show even further lag times (Henriksen et al. 1989).

Because soil acidification is affected by several interacting processes, and the response times are on the order of years to decades, evaluation of critical loads and determination of future effects to forests and surface waters requires the use of mathematical models. Such models may be simple empirical models such as the acidification model of Henriksen (1980) or more complicated process-oriented models such as MAGIC (Model for Acidification of Groundwater In Catchments) (Cosby et al. 1985a, 1985b) and MACAL (Model to Assess a Critical Acid Load) (de Vries 1988). These process models require information regarding present-day soil chemistry and physical properties of the soils characteristic for the catchment or site to be modelled. Herein lies one of the major dilemmas of mapping critical loads: soil heterogeneity both horizontally and vertically creates great difficulties in deriving soil characteristics representative for large areas. Surface waters, on the other hand, integrate over space and time runoff from entire catchments at scales of about 0.1 ha and larger.

Here we explore alternative methods for determining sulfur critical loads for soil in Norway. We use data for both water and soil chemistry at a catchment scale to derive estimates of soil acidification for soil characteristic of the entire catchment. We estimate critical load by means of the dynamic MAGIC model and the static empirical model of Henriksen (1980) and evaluate with respect to criteria for adverse effects to both forests and to surface waters. This procedure is applied to the data from 9 catchments in Norway; 4 catchments (Birkenes, Storgama, Langtjern, Kårvatn) currently monitored as part of SFT's programme, 4 catchments intensively studied for several years as part of SFT's programme (Vikedal, Gaular, Naustdal), and 2 catchments (Risdalsheia, Sogndal) of the RAIN project (Wright et al. 1988) (Figure 1).

2. Descriptions of models used

2.1 MAGIC

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 focusses 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, CO_2 dissolution, precipitation and dissolution of aluminum, chemical weathering, uptake and release of cations by vegetation, and export in runoff.

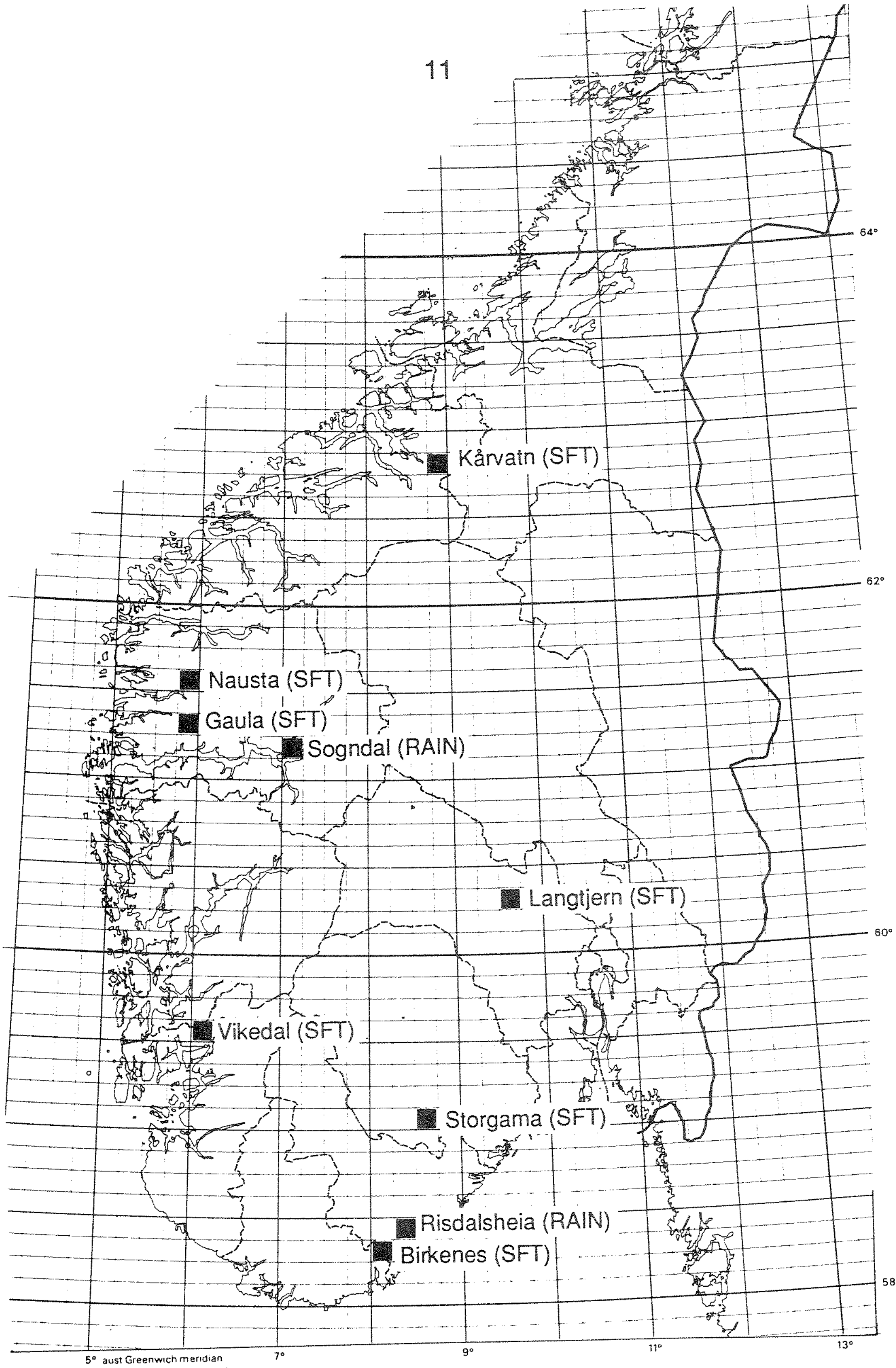


Figure 1. Map of southern Norway showing the grid used for mapping critical loads and the locations of the calibrated catchments for which soil and water chemistry data are available. SFT refers to sites included in the monitoring program run by the Norwegian State Pollution Control Authority (SFT 1984, 1986, 1988, 1989); RAIN refers to sites run by the Norwegian Institute for Water Research as part of the RAIN project (Wright et al. 1988).

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 Wright et al. 1986, Neal et al. 1988) and changes in regional lake chemistry in southern Norway (Wright, Cosby and Hornberger in review). In addition several of the assumptions in MAGIC have been tested experimentally (Grieve 1989). MAGIC is one of several dynamic models included in the UN-ECE Handbook on Mapping Critical Loads (Henriksen et al. 1989). Together these applications indicate that MAGIC provides a robust tool for predicting future soil and water acidification following changes in acid deposition.

In the applications to the Norwegian sites here we use an optimization procedure to calibrate MAGIC (Jenkins and Cosby 1989). We use soils data, precipitation data, streamwater data and estimated acid deposition history at each site together with the optimization routine to produce a calibrated model for each site. The optimization routine determines the set of initial saturation and weathering rates for each of the 4 base cations for the assumed pre-acidification condition in 1845. This set of initial values when run forward 140 years in time to the present (1985) produces the best fit to the present-day measured streamwater and soil chemistry. The calibrated model at each site is then used to predict future soil and water acidification 0-50 years into the future given various deposition scenarios.

The critical loads for each site are calculated using the MAGIC model under the condition that 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 alk = 0 (fish) or Al/Ca = 1.5 (forest) is met. This deposition is the critical load for sulfur. For all cases it is assumed that the loading and retention of nitrogen compounds are not changed from present-day conditions.

2.2 Empirical model

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.

This empirical model has also been extensively used in both North America and Europe. Typical applications include lakes in southernmost Norway (Wright and Henriksen 1983, Henriksen et al. 1988), lakes in the Austrian alps (Honsig-Erlenburg and Psenner 1986), and lakes in the eastern USA (Wright 1988). The empirical model is one of the static models included in the UN-ECE handbook (Sverdrup et al. 1989), and is currently being used in conjunction with mapping critical loads for freshwaters in Norway.

3. Site descriptions and data sources

3.1 Site descriptions

Operationally the 9 sites fall into 3 groups: (A) 4 small catchments (Birkenes, Storgama, Langtjern, Kårvatn) currently operated as long-term monitoring sites as part of SFT's National Environmental Monitoring Programme, (B) 3 large catchments (Vikedal, Gaular, Naustdal) investigated intensively for 1-4 years as part of SFT's National Environmental Monitoring Programme, and (C) 2 very small catchments (Risdalsheia, Sogndal) currently operated at part of the RAIN project.

The 4 catchments of group A range in area from 0.4 to 25 km^2, are all located on granitic-gneissic bedrock with thin and patchy soils. The 3 catchments of group B are much larger in area ranging from 120 to 670 km^2. These catchments are also characterized by granitic-gneissic bedrock and thin and patchy soils.

The 2 catchments of group C are the untreated reference catchments of the RAIN project (Reversing Acidification In Norway). The Risdalsheia site is characterized by exposed granitic bedrock and thin, organic-rich, truncated podzolic soils, and sparse cover of pine (Pinus sylvestris L.) and birch (Betula pubescens L.) (Lotse and Otabbong 1985). The Sogndal site is located 900 m above sea level and on gneissic bedrock with patchy, thin and poorly-developed soils and alpine vegetation (Wright et al. 1988).

3.2 Soil data

Soil data for the 7 sites in groups A and B come from NISK and were acquired as part of SFT's National Environmental Monitoring Programme. Generally two types of soil samples were collected at each site. Pits were excavated at 3-5 locations and soil samples collected from each of up to 7 soil horizons (O, A, E, Bh, Bs, BC and C). Multiple soil cores were taken at 50 points from a defined area (usually 10 x 20 m) near each pit and bulked by depth into 5 depth intervals. This was repeated 4 times at each plot. Chemical analysis proceeded by routine procedures in use at NISK (Ogner et al. 1984) and include bulk density, cation exchange capacity, and exchangeable Ca, Mg, Na, and K.

Soil data for the 2 RAIN project sites come from Lotse and Otabbong (1985) and Lotse (1989). In the RAIN project soil samples are collected annually from each catchment. At Risdalsheia the samples are collected at each point in 2-m grid, separated into 3 depth intervals (0-15, 15-30, and >30cm), and pooled into 5-7 samples per catchment. At Sogndal samples are collected by depth interval from each of 11 pits. Chemical analysis proceeds by routine methods at the Swedish Agricultural University (SLU) as described by Lotse and Otabbong (1985).

The MAGIC model requires estimates of these key soil parameters characteristic for an entire catchment. The data for the individual soil horizons and depths were aggregated both spatially and with depth at each catchment to obtain single values for each parameter. The mean of logarithmic-transformed or mean of square-root transformed data was used to compensate for skewness in the data. Details of the analysis and aggregation of the soils data for the RAIN sites are given in Reuss (1989).

Table 1. Catchment and soil parameters used in application of MAGIC to calibrated catchments in Norway. Data from Wright et al. (1988), and SFT (1984, 1986, 1988, 1989).

Parameter	Units	Birkenes	Storgama	Langtjern	Kaarvatn	Vikedal	Gaular	Naustdal	Sogndal	Risdals.
catchment area	km2	0.41	0.60	4.56	25	119	630	274	0.09	0.00022
precipitation	mm/yr	1470	1010	725	2000	2390	1400	2120	923	1400
runoff	mm/yr	1190	970	605	1830	2115	1125	2000	870	1230
soil depth	m	0.40	0.32	0.40	0.29	0.75	0.75	0.75	0.30	0.11
porosity	%	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
bulk density	kg/m3	936	503	828	764	1036	955	800	618	400
CEC	meq/kg	46	121	63	91	23	38	62	37	82
SO4 ads. half-sat.	meq/m3	110	80	100	60	60	60	60	60	60
SO4 ads. max-capacity	meq/kg	1	1	1	6	6	6	6	6	6
solubility Al(OH)3	log	8.2	8.1	8.2	8.8	8.8	8.6	8.6	8.8	7.6
select. coeff. Al-Ca	log	0.5	0.2	1.4	1.1	0.1	0.3	1.4	-1.2	-1.9
select. coeff. Al-Mg	log	0.6	-0.5	1.6	0.7	0.8	1.6	2.0	-0.1	-0.3
select. coeff. Al-Na	log	-1.9	-1.7	-2.2	-0.5	-1.5	-1.6	-2.2	-2.0	-1.7
select. coeff. Al-K	log	-5.8	-4.3	-6.0	-5.0	-6.3	-4.8	-4.1	-6.1	-6.0
total organics, solution	mmol/m3	65	90	60	20	20	20	20	20	75
organic pK1	-log	4.5	4.7	4.5	4.0	4.5	4.5	4.5	4.0	4.5
organic pK2	-log	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
CO2, soil air	atm	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.002
soil temperature	oC	5.0	5.0	5.0	6.6	6.6	6.6	6.6	6.6	7.0
CO2, streamwater	atm	0.0007	0.0007	0.0007	0.0025	0.0011	0.0011	0.0011	0.0011	0.0008
stream temperature	oC	5.0	5.0	5.0	6.6	6.6	6.6	6.6	6.6	7.0

Table 2. Results of MAGIC applications to calibrated catchments in Norway.

Parameter	Units	Birkenes	Storgama	Langtjern	Kaarvatn	Vikedal	Gaular	Naustdal	Sogndal	Risdals.
Ca saturation, soil 1983/4	%	3.2	3.3	3.7	5.9	3.8	7.5	7.9	17.5	5.5
Mg saturation, soil 1983/4	%	1.7	2.2	1.6	5.3	2.6	1.7	3.6	3.9	2.7
Na saturation, soil 1983/4	%	2.0	0.7	1.0	0.8	2.0	1.7	4.4	2.0	1.4
K saturation, soil 1983/4	%	2.1	0.7	2.6	1.8	2.2	2.0	2.4	3.0	1.9
total base saturation 1983/4	%	9.0	6.9	8.9	13.8	10.6	12.9	18.3	26.4	11.5
Ca saturation, soil 1844	%	20.6	9.0	8.8	7.2	9.0	8.7	10.2	20.6	24.4
Mg saturation, soil 1844	%	12.3	4.4	3.3	6.3	7.3	2.4	5.1	5.4	13.0
Na saturation, soil 1844	%	6.0	1.0	1.9	0.9	3.6	2.1	5.6	2.6	3.0
K saturation, soil 1844	%	3.2	1.1	2.8	1.9	2.7	2.2	2.8	3.3	3.9
total base saturation 1844	%	42.1	15.5	16.8	16.3	22.6	15.4	23.7	31.9	44.3
Ca weathering	meq/m2/y	25.0	10.4	12.0	23.2	14.0	11.9	29.2	5.5	4.0
Mg weathering	meq/m2/y	2.3	0.3	2.3	2.9	2.1	0.1	2.9	1.0	2.2
Na weathering	meq/m2/y	3.7	0.0	6.5	8.0	2.5	1.6	0.0	4.7	2.4
K weathering	meq/m2/y	0.5	0.0	0.0	2.2	0.5	2.6	9.1	0.5	1.2
total weathering	meq/m2/y	31.5	10.7	20.8	36.3	19.1	16.2	41.2	11.7	9.8
Ca* deposition	meq/m2/y	16.8	10.0	6.5	7.3	12.3	0.7	4.6	4.5	9.3
Mg* deposition	meq/m2/y	0.0	0.5	0.9	0.2	1.0	-0.6	1.3	-1.0	2.7
Na* deposition	meq/m2/y	2.2	2.0	0.0	0.0	0.0	0.0	1.0	2.1	-10.3
K* deposition	meq/m2/y	7.6	2.8	3.3	1.6	2.9	0.8	1.7	1.2	1.7
total BC* deposition	meq/m2/y	26.6	15.3	10.7	9.1	16.2	0.9	8.6	6.8	3.4
BC* weathering + dep	meq/m2/y	58.1	26.0	31.5	45.4	35.3	17.1	49.8	18.5	13.2
SO4* deposition	meq/m2/y	146	69	44	15	76	28	50	17	101

The catchment and soil parameters used to calibrate MAGIC were measured or estimated at each of the 9 sites or in the case of lacking information were assumed equal to those for the RAIN sites at Sogndal and Risdalsheia (Table 1). MAGIC output for each site includes estimates of pre-acidification base saturation and weathering rates (Table 2).

3.3 Precipitation and water chemistry data

Wet and dry atmospheric inputs and annual streamwater outputs are reported for Vikedal (SFT 1984), Gaular (SFT 1986), Naustdal (SFT 1988), Birkenes, Storgama, Langtjern, and Kårvatn (SFT 1989), and Risdalsheia and Sogndal (Wright et al. 1988). Volume-weighted average data for multiple years are used when the data are available. Dry deposition is estimated from input-output budgets using the Cl balance procedure in which inputs of all ions are multiplied by the ratio of output/input measured for Cl. For the RAIN sites dry deposit of seasalts is estimated by this method, while nitrogen and sulfur compounds are calculated from measured concentrations of gases and particles and assumed deposition velocities (Wright et al. 1988).

Calculation of critical load by the empirical model follows the procedure outlined in the UN-ECE Manual (Sverdrup et al. 1989). Here only 5 values for each catchment are needed: annual runoff volume, and the volume-weighted mean concentrations of base cations, Cl, SO_4, and alkalinity (Table 3).

4. Results

4.1 Birkenes

A total of 13 years of input-output data were used to obtain weighted-mean fluxes at Birkenes (Table 4). For the MAGIC calibration the soils data were combined to obtain single values for the catchment (Table 4).

Table 3. Calculation of critical load for sulfur (fish criterion of alkalinity = 0) by the emprical model (Henriksen 1980) with variable F-factor (Henriksen et al. 1988). Units: μeq/l. The first 5 values are measured (annual runoff, volume-weighted mean concentrations of sum base cations SBC, Cl, SO$_4$, and alkalinity) and the remaining are calculated (see Sverdrup et al. 1989).

		Birkenes	Storgama	Langtjern	Kaarvatn	Vikedal	Gaular	Naustdal	Sogndal	Risdals.
runoff	m/yr	1.19	0.97	0.61	1.83	2.12	1.12	2.00	0.88	1.24
SBC 1985	ueq/l	212	80	98	85	156	90	117	79	147
Cl 1985	ueq/l	123	32	17	51	117	55	68	44	110
SO4 1985	ueq/l	134	74	75	16	47	25	31	24	93
alk 1985	ueq/l	-55	-37	5	18	-18	4	6	4	-81
SBC* 1985	= SBC -(1.11 x Cl)	75	44	79	28	26	29	42	30	25
F-factor	= sin(SBC*/400 x 90)	0.29	0.17	0.31	0.11	0.10	0.11	0.16	0.12	0.10
SO4*	= SO4 -(1.03 x Cl)	121	71	73	11	35	19	24	19	82
critical load condition alk = 0										
required change alk =	0 - alk 1985	55	37	-5	-18	18	-4	-6	-4	81
F-factor	= change SBC*/change SO4*	0.29	0.17	0.31	0.11	0.10	0.11	0.16	0.12	0.10
change SO4*	= change alk + change SBC*									
change SO4*	= change alk /(1-F)	78	45	-7	-20	20	-5	-7	-5	90
critical conc. SO4* ueq/l										
	= SO4* 1985 - change SO4*	44	26	80	31	15	24	31	24	-8
critical load SO4* meq/m2/yr										
	= critical conc. SO4* x runoff in m/yr	52	25	49	57	32	27	62	21	-10

The calculated critical loads for non-marine sulfur for Birkenes are 41 meq/m^2/yr (fish, MAGIC), 52 meq/m^2/yr (fish, empirical), and 153 meq/m^2/yr (forest, MAGIC). The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

The stream draining the catchment at Birkenes has been highly acidified since the beginning of measurements in 1971. Birkenes is located in Norway's area of maximum acid deposition (present-day deposition 146 meq/m^2/yr). Historical information from the site and from lakes in the vicinity indicate that fish populations were affected already in the 1940's.

MAGIC calibration to the data from Birkenes is consistent with this picture. The model indicates that volume-weighted mean alkalinity fell below zero around 1950 (Figure 2). This implies that there were frequent acid episodes prior to this time.

The critical load for Birkenes has thus been exceeded for many years, at least as far as the fish criterion is concerned. A 70% reduction in sulfur deposition relative to present-day loadings is required to restore the stream at Birkenes within 50 years such that alkalinity again increases above zero (Figure 2).

The MAGIC calibration further suggests that the critical load with respect to the forest criterion is nearly exceeded at present-day levels of sulfur deposition (Figure 2). Indeed only a 5% increase in current deposition is apparently required to exceed this critical load.

These calculations are made assuming that nitrogen leaching in the future occurs at the same rate as today. If, however, nitrate leaching increases as it has generally in southernmost Norway over the past 12 years, then the critical load of sulfur with respect to forest will be exceeded at present-day loadings or even slightly reduced loadings. Thus assuming that the forest criterion used here is correct, then there is good reason to fear for the health of the spruce forest at Birkenes.

Table 4. Birkenes. Upper panel: input-output data used to calibrate the MAGIC model. Data from SFT (1989) p. 267. Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. To calibrate MAGIC Mg deposition = 28, SO_4 deposition = 161, and K uptake = 70% were used. Lower panel: soils data used to calibrate the MAGIC model.

	Input fluxes. Wet precipitation.					Output fluxes				Conc.
Yr.	73-78	81-83 85-87	88	mean	Cl-corr conc.	73-78	81-83 85-87	1988	mean	ueq/l
H2O	1352	1504	1986	1471	2489	1041	1264	1644	1190	1190
H+	78	77	113	80	136	34	36	37	35	30
Na	73	76	87	75	128	125	135	195	135	113
K	5	7	8	6	10	7	6	12	7	6
Ca	12	14	15	13	22	65	66	78	66	56
Mg	17	20	21	19	32	43	39	47	41	35
Al						73	70	77	72	60
NH4	52	61	87	59	100			9	1	1
SO4	98	95	103	97	164	158	157	184	160	134
Cl	82	89	98	86	146	136	147	204	146	123
NO3	53	56	83	57	96	7	11	19	10	8
SBC	159	178	218	172	292	240	246	341	251	210
SSA	233	240	284	240	406	301	315	407	316	265
ALK	-74	-62	-66	-68	-115	-61	-69	-66	-65	-55
A-						46	37	48	42	35

Birkenes soil summary

Depths: A. Stuanes Means: J. Reuss Table 3

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
O	8	266	322	18.9	9.1	1.5	3.8	33.2
Ah	7	1063	36	4.1	2.0	1.8	2.7	10.7
E	8	963	53	2.3	1.2	1.3	1.4	6.2
B	12	1029	25	1.3	1.3	1.9	2.2	6.6
C	5	1560	7	2.2	0.7	3.0	1.6	7.4
Total mean	40	936	46	3.2	1.7	2.0	2.1	9.0

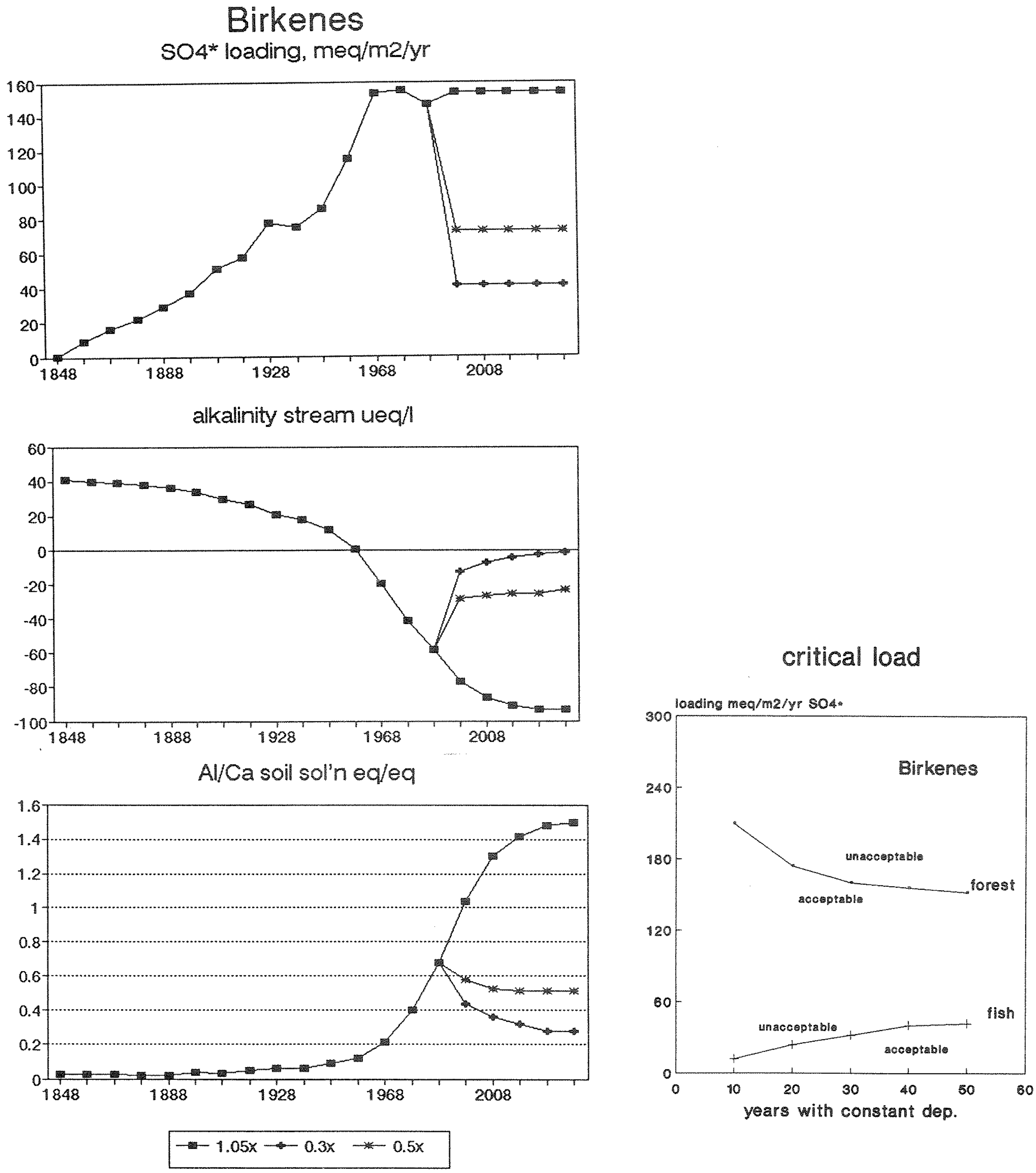


Figure 2. Birkenes. Sulfate loading (top panel), stream alkalinity (middle panel) and Al/Ca equivalent ratio in soil solution (lower panel) as predicted by the MAGIC model. Future predictions are made using 3 scenario in which the deposition is changed from present-day levels and held constant for 50 years. The critical load for soil at Birkenes (right panel) is time-dependent. The critical load criteria for fish (stream alkalinity > 0) and forest (Al/Ca in soil solution < 1.5).

4.2 Storgama

A total of 13 years of input-output data were used to obtain weighted-mean fluxes at Storgama (Table 5). The precipitation station is at Treungen. Present deposition of non-marine SO_4 is 69 meq/m^2/yr. For the MAGIC calibration the soils data were combined to obtain single values for the catchment (Table 5).

The calculated critical loads for non-marine sulfur for Storgama are 21 meq/m^2/yr (fish, MAGIC), 25 meq/m^2/yr (fish, empirical), and 76 meq/m^2/yr (forest, MAGIC). The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

The stream at Storgama is highly acidified, and lakes and streams in the vicinity have been barren of fish since the 1940-50's. This is consistent with the MAGIC reconstruction of alkalinity; weighted-average alkalinity drops below zero in the 1940's (Figure 3). At Storgama a 70% reduction in sulfur loading relative to present-day rates is required to restore the stream to the point at which alkalinity increases to above zero after 50 years (Figure 3).

Also at Storgama the MAGIC calibration indicates that the present-day loading of sulfur is very close to the critical load for the forest criterion (Figure 3). Indeed a 10% increase above present-day sulfur loadings is apparently sufficient to exceed the critical load after 50 years. Again this calculation assumes that nitrogen uptake in the catchment occurs at present-day rates; if nitrogen leaching increases, then the critical load for sulfur becomes even lower.

4.3 Langtjern

A total of 14 years of input-output data were used to obtain weighted-mean fluxes at Langtjern (Table 6). Precipitation is collected at Gulsvik. Present deposition of non-marine SO_4 is 44 meq/m^2/yr. The output data are for the lake outlet. For MAGIC calibration soils data were combined to obtain single values

Table 5. Storgama. Upper panel: input-output data used to calibrate the MAGIC model. Data from SFT (1989) p. 266. Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. To calibrate MAGIC Mg deposition = 6 and SO_4 deposition = 72 were used. Lower panel: soils data used to calibrate the MAGIC model.

	Input fluxes meq/m2					Output fluxes meq/m2				conc.
	75-78	80-87	88	mean	Cl-corr	75-78	80-87	88	mean	ueq/l
H2O	924	1009	1348	1009	1838	831	994	1346	971	971
H+	51	52	73	53	97	27	30	37	30	31
Na	13	17	16	16	29	29	26	38	28	29
K	2	2	2	2	4	6	4	3	5	5
Ca	6	7	7	7	12	33	33	34	33	34
Mg	4	5	6	5	9	13	12	13	12	13
Al						16	19	20	18	19
NH4	25	31	44	30	55			6	0	0
SO4	53	55	63	55	100	67	73	77	71	74
Cl	16	17	19	17	31	28	31	39	31	32
NO3	27	29	48	30	54	11	11	15	11	12
HCO3										
SBC	25	31	31	29	53	81	75	88	78	80
SAA	96	101	130	102	185	106	115	131	113	117
alk	-71	-70	-99	-73	-132	-25	-40	-43	-36	-37
A-						18	9	14	12	13

Storgama soil summary
Depths: A. Stuanes Means: J. Reuss Table 3

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
H1	15	235	259	7.5	4.64	1	1	14.1
H2	8	354	247	2.76	2.48	0.5	0.5	6.2
Ah,Bs	9	1083	35	2.01	1.2	0.62	0.62	4.5
C,BC	0	0	0	0	0	0	0	0.0
IIC	0	0	0	0	0	0	0	0.0
Total mean	32	503	121	3.3	2.2	0.7	0.7	6.9

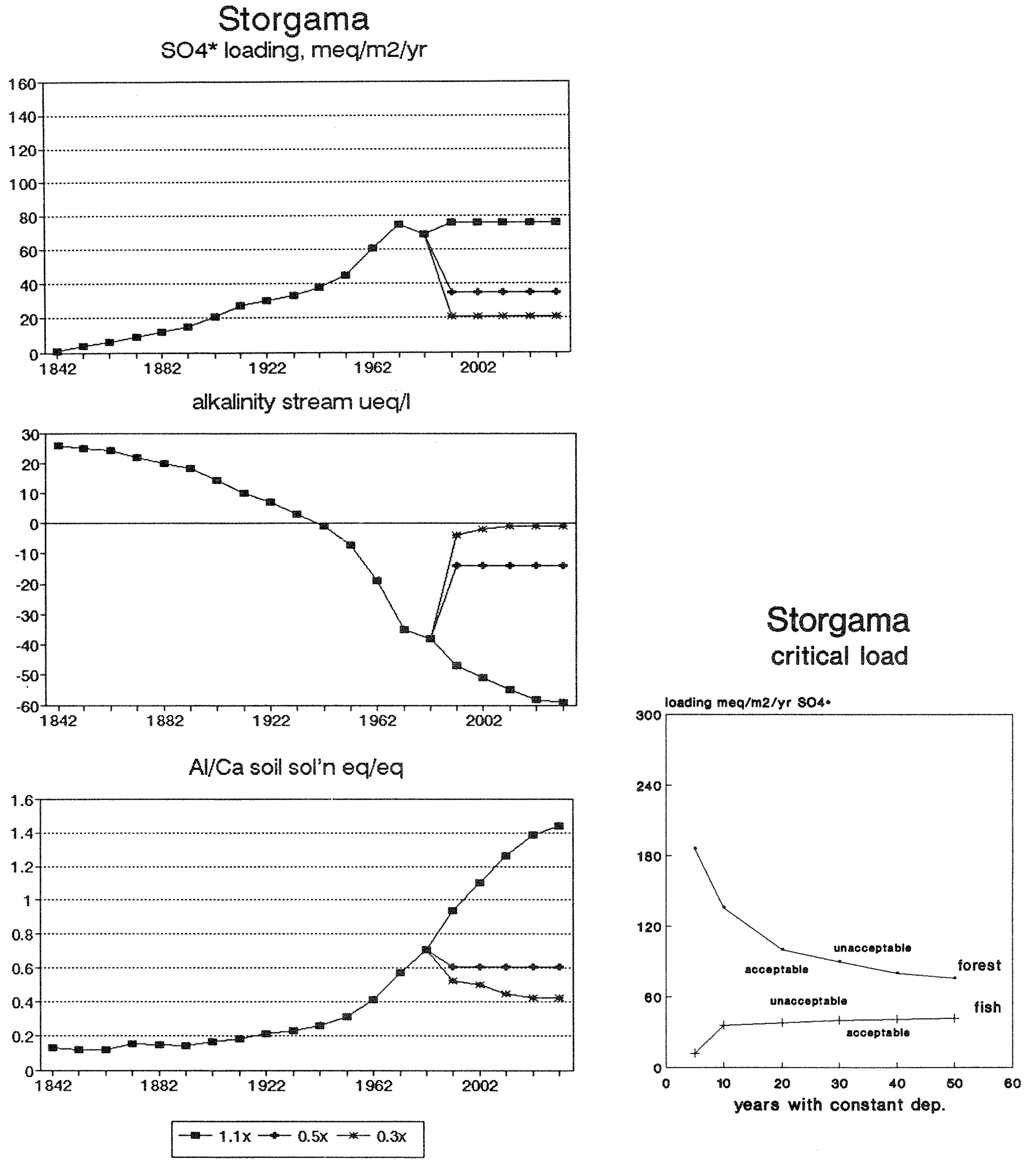


Figure 3. Storgama. (See text to Figure 2)

for the catchment (Table 6).

The calculated critical loads for non-marine sulfur for Langtjern are 29 meq/m^2/yr (fish, MAGIC), 49 meq/m^2/yr (fish, empirical), and 80 meq/m^2/yr (forest, MAGIC). The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

The lake Langtjern is highly colored and acidified. Natural fish reproduction in the lake ceased in the 1960's, but stocked fish can still survive today. The lake is thus today near the critical load. This is consistent with the MAGIC reconstruction of alkalinity; weighted-average alkalinity drops from pre-acidification levels of about 40 μeq/l to just above zero in the 1980's. (Figure 4). At Langtjern a 35% reduction in sulfur loading relative to present-day rates is required to maintain positive alkalinity over the next 50 years (Figure 4).

At Langtjern the MAGIC calibration indicates that a 1.8x increase in the present-day loading of sulfur over 50 years is the critical load with respect to the forest criterion (Figure 4). Again this calculation assumes that nitrogen uptake in the catchment occurs at present-day rates; if nitrogen leaching increases, then the critical load for sulfur must be decreased accordingly.

4.4 Kårvatn

A total of 10 years of input-output data were used to obtain weighted-mean fluxes at Kårvatn (Table 7). The runoff station is located on the river Nauståa, near Todalen, at the bottom of the catchment. For the MAGIC calibration the soils data were combined to obtain single values for the catchment (Table 7).

The calculated critical loads for non-marine sulfur for Kårvatn are 64 meq/m^2/yr (fish, MAGIC), 57 meq/m^2/yr (fish, empirical), and 125 meq/m^2/yr (forest, MAGIC). The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

Table 6. Langtjern. Upper panel: input-output data used to calibrate the MAGIC model. Data from SFT (1989) p. 268. Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. To calibrate MAGIC Cl dry deposition factor = 1.3 and K uptake = 70% were used. Lower panel: soils data used to calibrate the MAGIC model.

	Input fluxes				Output fluxes			
	75-83 83-87	88	mean	S-corr	75-83 83-87	88	mean	conc ueq/l
H2O	702	1023	725	815	585	886	607	607
H+	34	48	35	39	12	20	13	21
Na	5	6	5	6	14	17	14	23
K	3	3	3	3	2	3	2	3
Ca	6	5	6	7	33	37	33	55
Mg	2	2	2	2	10	11	10	17
Al			0	0	13	15	13	22
NH4	22	28	22	25		1	0	0
SO4	40	43	40	45	45	48	45	75
Cl	7	8	7	8	10	11	10	17
NO3	20	30	21	23	1	2	1	2
HCO3								
SBC	16	16	16	18	59	68	60	98
SAA	67	81	68	76	56	61	56	93
ALK	-51	-65	-52	-58	3	7	3	5
A-					28	43	29	48

Langtjern soil summary
Depths: A. Stuanes Means: J. Reuss Table 3

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
Ol/f	5	178	353	31.9	8.0	0.4	6.4	46.8
Oh, O	6	331	273	2.3	2.3	0.5	4.1	9.2
E	5	1173	28	3.1	1.5	0.6	2.1	7.2
Bh, Bs	19	883	61	1.9	1.5	0.7	2.5	6.6
2CB, 2C	6	1437	9	4.9	0.9	2.0	2.3	10.1
Total mean	40	828	63	3.7	1.6	1.0	2.6	8.8

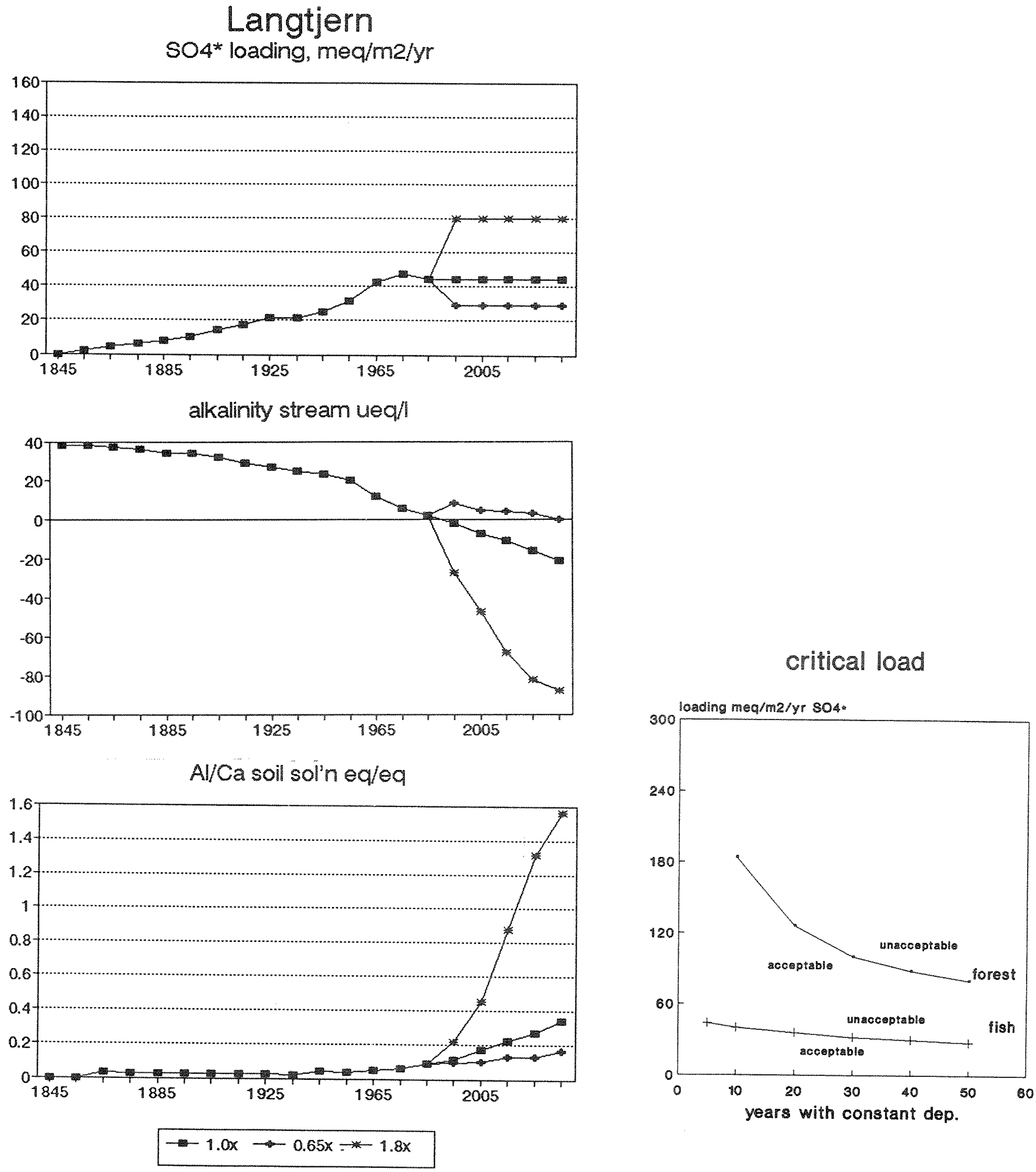


Figure 4. Langtjern. (See text to Figure 2)

Kårvatn is the most pristine of all the sites treated here. Present-day deposition of non-marine sulfur is only 16 meq/m^2/yr. Surface waters are essentially unaffected in this area.

At Kårvatn the MAGIC calibration indicates that a 3.5x increase in the present-day loading of sulfur over 50 years is the critical load with respect to the fish criterion (Figure 5); the corresponding figure for the forest criterion is 7x. Again these calculations assume that nitrogen uptake in the catchment occurs at present-day rates; if nitrogen leaching increases, then the critical load for sulfur must be decreased accordingly.

4.5 Vikedal

A total of 4 years of input-output data were used to obtain weighted-mean fluxes at Vikedal (Table 8). Data for the station at Røyravatn were used. This is well upstream from the ongoing liming activities at Vikedal. For the MAGIC calibration the soils data were combined to obtain single values for the catchment (Table 8).

The calculated critical loads for non-marine sulfur for Vikedal are 15 meq/m^2/yr (fish, MAGIC), 32 meq/m^2/yr (fish, empirical), and 100 meq/m^2/yr (forest, MAGIC). Present-day deposition is 77 meq/m^2/yr. The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

Vikedal is one of the most sensitive sites included in this study. The catchment is sensitive due to the combination of soils with low cation exchange capacity and low base saturation, low weathering rates, high amounts of precipitation, and the fact that the original pool of base cations has been substantially depleted due to decades of acid deposition.

The upper reaches of the river Vikedal are acidified, and high elevation lakes and streams in the catchment have been barren of fish for several decades. In recent years salmon and sea-trout in the lower reaches have also been affected.

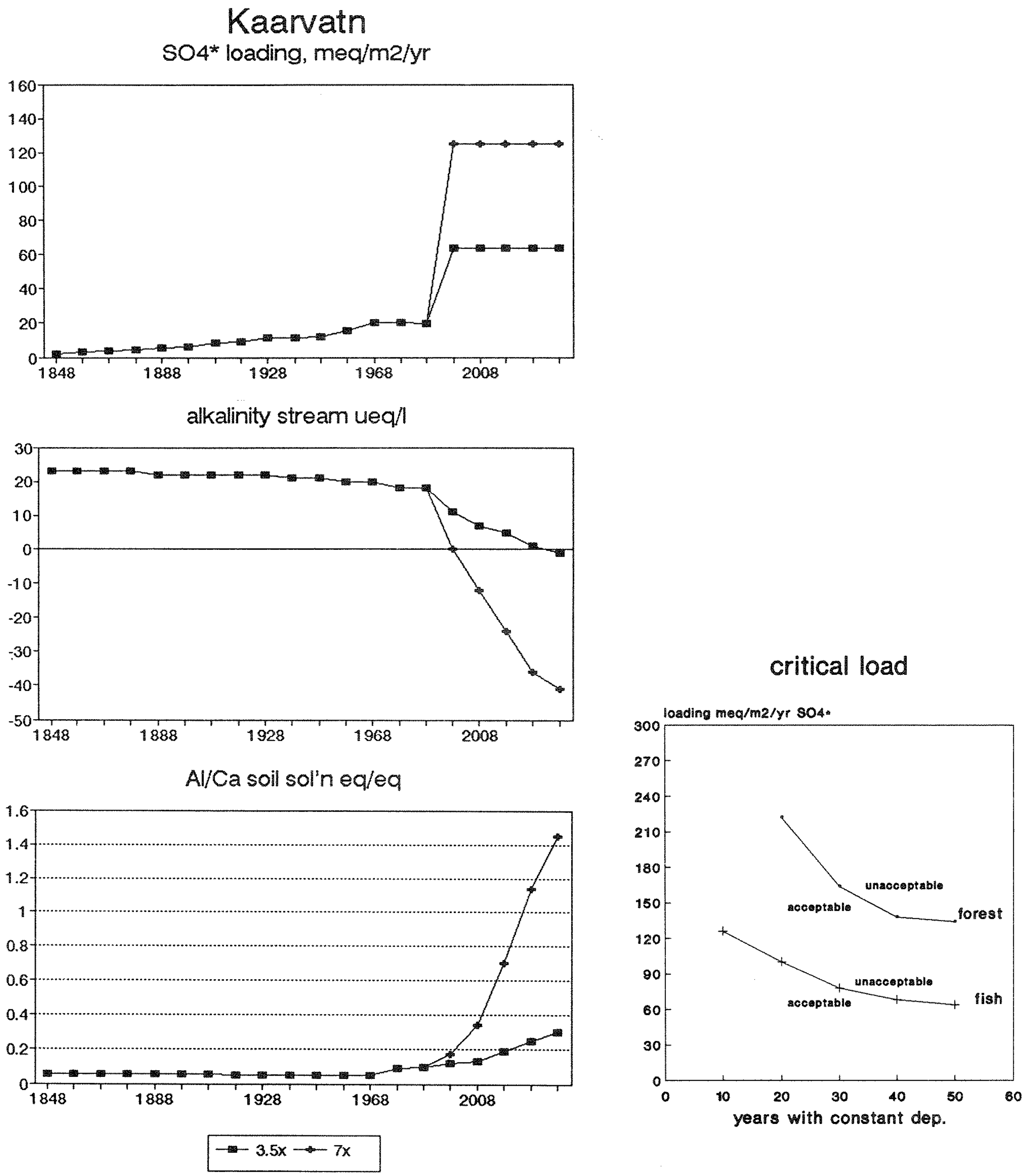
Table 7. Kårvatn. Upper panel: input-output data used to calibrate the MAGIC model. Data from SFT (1989) p. 269. Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. To calibrate MAGIC SO_4 dry deposition factor = 1.2 was used. Lower panel: soils data used to calibrate the MAGIC model.

	Input fluxes				Output fluxes			conc.
Yr.	78-84 86-87	88	mean	Cl-corr	78-84 86-87	88	mean	ueq/l
H2O	1307	1550	1331		1795	2154	1831	1831
H+	16	13	16	17	2	2	2	1
Na	70	106	74	79	87	87	87	48
K	3	4	3	3	6	6	6	3
Ca	10	10	10	11	38	42	38	21
Mg	16	22	17	18	24	27	24	13
Al					6	5	6	3
NH4	9	10	9	10		1	0	0
SO4	24	10	23	24	29	32	29	16
Cl	83	119	87	93	93	88	93	51
NO3	6	7	6	7	1	2	1	1
HCO3					36	35	36	20
SBC	108	152	112	120	155	163	156	85
SAA	113	136	115	123	123	122	123	67
alk	-5	16	-3	-3	32	41	33	18
A-					4	13	5	3

Kaarvatn soil summary

Depths: A. Stuanes Means: J. Reuss Table 3 (density), Table 2 (rest)

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
O	4	331	212.86	19.0	20.4	1.4	7.5	48.3
Ah	10	418	189.01	14.9	17.6	1.4	4.5	38.4
E	2	990	29.56	7.1	4.7	1.1	2.3	15.2
Bh	5	978	89.29	2.7	1.7	0.5	0.6	5.5
Bs/BC	14	1026	59.64	3.0	1.7	0.6	0.8	6.1
Total mean	35	764	91	5.9	5.3	0.8	1.8	13.8



Kaarvatn

SO4* loading, meq/m2/yr

alkalinity stream ueq/l

Al/Ca soil sol'n eq/eq

critical load

Figure 5. Kårvatn. (See text to Figure 2)

This is consistent with the MAGIC reconstruction of alkalinity at the station Røyravatn; weighted-average alkalinity drops below zero in the 1950's (Figure 6). At Vikedal a 80% reduction in sulfur loading relative to present-day rates is required to restore the stream to the point at which alkalinity increases to above zero after 50 years (Figure 6).

Also at Vikedal the MAGIC calibration indicates that the present-day loading of sulfur is very close to the critical load for the forest criterion (Figure 6). A 20% increase above present-day sulfur loadings is apparently sufficient to exceed the critical load after 50 years. Again this calculation assumes that nitrogen uptake in the catchment occurs at present-day rates; if nitrogen leaching increases, then the critical load for sulfur becomes even lower.

4.6 Gaular

Only 1 year of input-output data is available for Gaular (Table 9). The station at the outlet of Føllingsvatn (locality 57.3) was chosen. For the MAGIC calibration the soils data were combined to obtain single values for the catchment (Table 9).

The calculated critical loads for non-marine sulfur for Gaular are 28 meq/m^2/yr (fish, MAGIC), 27 meq/m^2/yr (fish, empirical), and 120 meq/m^2/yr (forest, MAGIC). The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

Gaular is a catchment currently at the threshold of acidification effects. Fish populations have been affected in several lakes in the catchment, and episodes of fish kills have been reported. The catchment is classed as endangered (SFT 1986).

At Gaular the MAGIC calibration indicates that 50 years of continued non-marine sulfur deposition at the present-day rate of 20 meq/m^2/yr is sufficient

Table 8. Vikedal. Upper panel: input-output data used to calibrate the MAGIC model. Runoff data from SFT (1984) and precipitation data from SFT (1989). Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. To calibrate MAGIC SO_4 deposition = 102 and K uptake = 50% were used. Lower panel: soils data used to calibrate the MAGIC model.

	Input concentrations					flux	Cl-corr	Output	
			ueq/l			meq/m2	meq/m2	ueq/l	meq/m2
	1984	1985	1986	1987	mean	mean	mean	1982-3	1982-3
H2O	1932	2223	3017	1943	2391	2391	2491	2115	2115
H+	27	35	30	31	31	73	76	11	23
Na	90	72	93	65	85	203	212	102	216
K	3	3	3	3	3	7	7	3	6
Ca	10	9	7	6	9	21	22	23	49
Mg	21	16	21	15	19	46	48	28	59
Al								5	11
NH4	19	24	21	24	21	51	53		
SO4	43	47	46	44	45	108	113	47	99
Cl	105	84	109	76	99	237	247	117	247
NO3	17	21	18	19	19	45	47	10	21
HCO3									
SBC	124	100	124	89	116	277	289	156	330
SAA	165	152	173	139	163	390	407	174	368
alk	-41	-52	-49	-50	-47	-113	-118	-18	-38
A-								-2	-4

Vikedal soil summary

Depths: A. Stuanes Means: J. Reuss Table 5

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
O	5	243	280	26.5	20.1	1.7	4.4	52.6
Ah	7	753	58	10.6	11.1	1.7	5.7	29.0
E	6	1025	24	4.8	5.0	1.7	2.6	14.1
B	39	1042	21	2.5	1.8	1.8	1.9	7.9
C	19	1326	8	3.4	1.0	2.5	1.9	8.8
Total mean	75	1037	23	3.8	2.6	2.0	2.2	10.7

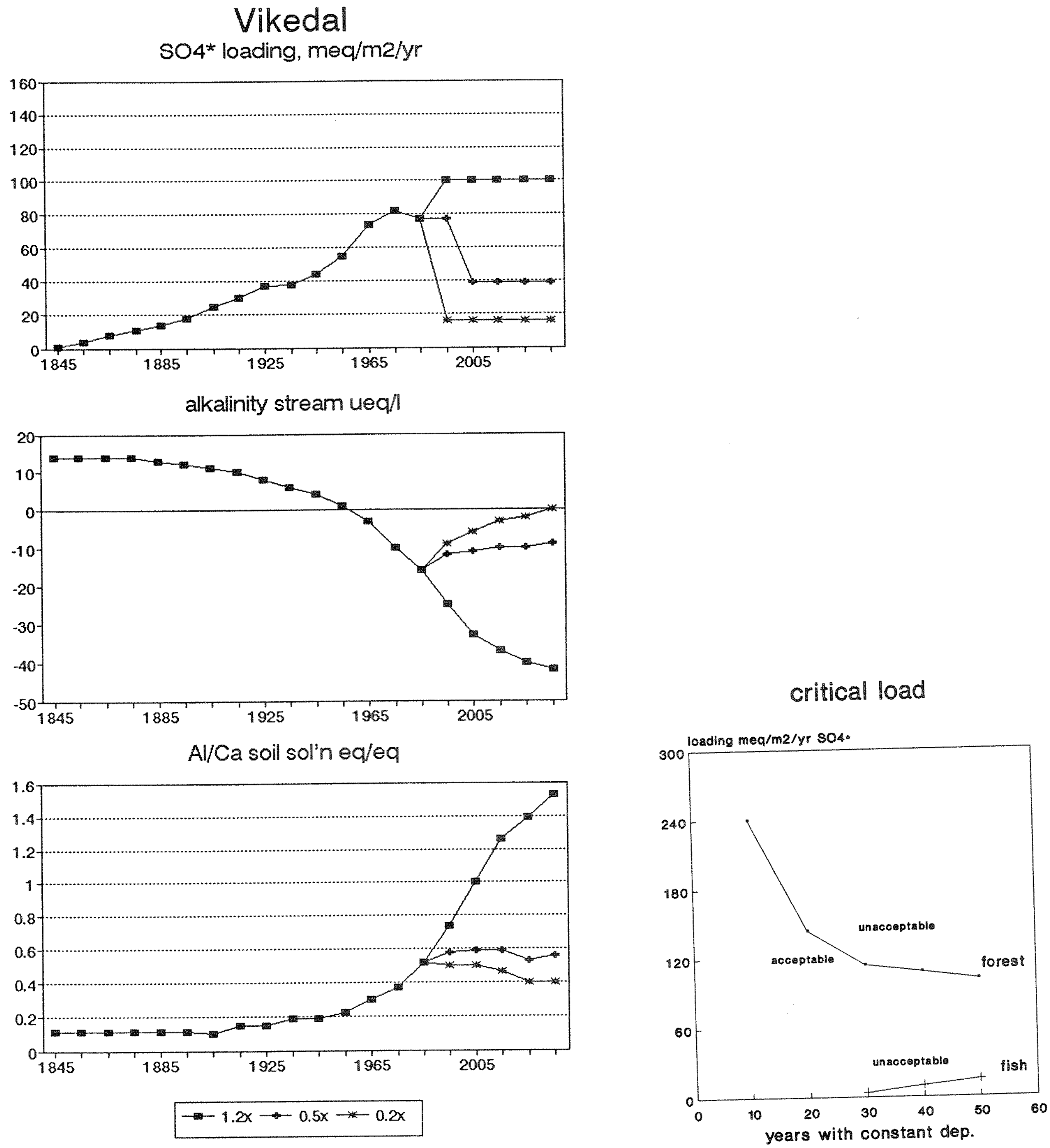


Figure 6. Vikedal. (See text to Figure 2)

Table 9. Gaular. Upper panel: input-output data used to calibrate the MAGIC model. Data from SFT (1986). Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. Lower panel: soils data used to calibrate the MAGIC model.

	Input	1984	1984	Output	1984
			Cl-korr.		
	ueq/l	meq/m2	meq/m2	ueq/l	meq/m2
H2O	1403	1403	1403	1125	1125
H+	18	25	18	3	3
Na	52	73	53	51	57
K	2	3	2	5	6
Ca	3	4	3	20	23
Mg	12	17	12	14	16
Al				2	2
NH4	12	17	12		
SO4	26	36	26	25	28
Cl	61	86	62	55	62
NO3	9	13	9	4	5
HCO3				2	2
SBC	81	114	82	90	101
SAA	96	135	97	86	97
alk	-15	-21	-15	4	5
A-				9	10

Gaular soil summary

Depths: A. Stuanes Means: J. Reuss Table 5 (density), Table 6 (rest)

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
O	14	245	335	29.8	15.8	1.2	5.2	51.9
Ah	2	658	107	20.2	13.3	0.9	4.3	38.6
E	9	1155	11	5.1	1.0	2.6	3.1	11.8
B	27	978	36	2.9	0.5	0.9	1.3	5.6
C	23	1303	12	9.4	0.8	2.1	1.9	14.2
Total mean	75	955	38	7.5	1.7	1.7	2.0	13.0

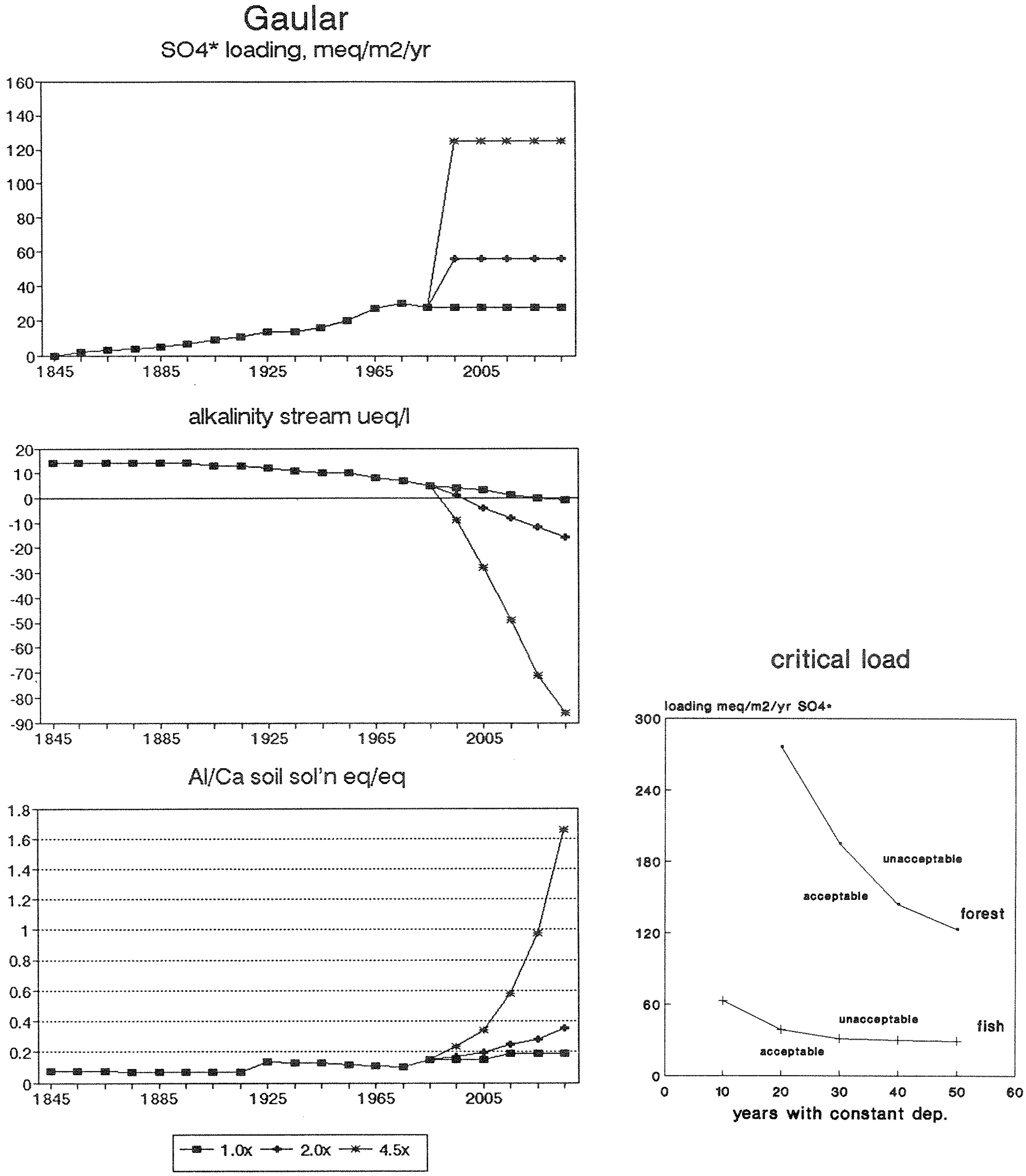


Figure 7. Gaular. (See text to Figure 2)

to lower the alkalinity to zero (Figure 7). The critical load with respect to the forest criterion is much higher; an increase of 4.5x can apparently be tolerated. Again these calculations assume that nitrogen uptake in the catchment occurs at present-day rates; if nitrogen leaching increases, then the critical load for sulfur must be decreased accordingly.

4.7 Naustdal

A total of 4 years of input-output data were used to obtain weighted-mean fluxes at Naustdal (Table 10). Here the station at Espeland (locality 34.1) was used. For the MAGIC calibration the soils data were combined to obtain single values for the catchment (Table 10).

The calculated critical loads for non-marine sulfur for Naustdal are 85 meq/m^2/yr (fish, MAGIC), 62 meq/m^2/yr (fish, empirical), and 190 meq/m^2/yr (forest, MAGIC). The MAGIC estimates are based on the situation after 50 years of constant deposition at these rates.

Naustdal is the least sensitive of all the sites treated here. The catchment as a whole has thicker soils (estimated 75 cm) and higher weathering rates (41 meq/m^2/yr for the 4 base cations) than the other sites. The catchment receives high amounts of precipitation, and thus present-day deposition of non-marine sulfur is 50 meq/m^2/yr, although concentrations of acid and sulfate in precipitation are low.

Intensive studies at Naustdal indicate adversely affected invertebrate and fish populations at several sites within the catchment (SFT 1988). The river itself is apparently not yet affected.

At Naustdal the MAGIC calibration indicates that a 1.7x increase in the present-day loading of sulfur over 50 years is the critical load with respect to the fish criterion (Figure 8); the corresponding figure for the forest criterion

Table 10. Naustdal. Upper panel: input-output data used to calibrate the MAGIC model. Runoff data from SFT (1988) and precipitation data from SFT (1989). Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. To calibrate MAGIC SO_4 deposition = 64 was used. Lower panel: soils data used to calibrate the MAGIC model.

	Input concentrations ueq/l					Flux		Output concentrations ueq/l				Flux
Yr.	1985	1986	1987	1988	mean	meq/m2	Cl-korr	1984	1985	1986	mean	meq/m2
H2O	1943	2314	1969	2253	2120	2120	2150				2000	2000
H+	20	18	19	21	20	41	42	2	1	1	1	3
Na	43	55	40	81	55	116	118	80	53	52	62	123
K	2	2	2	2	2	4	4	8	7	8	8	15
Ca	4	4	4	6	5	10	10	30	26	28	28	56
Mg	10	13	9	19	13	27	27	24	18	18	20	40
Al								1	0	1	1	1
NH4	6	6	8	6	7	14	14					
SO4	33	33	33	42	35	75	76	33	29	30	31	61
Cl	49	64	47	93	63	134	136	93	54	57	68	136
NO3	9	7	9	9	9	18	18	5	4	6	5	10
HCO3								8	11	9	9	19
SBC	65	80	63	114	81	171	173	142	104	106	117	235
SAA	91	104	89	144	107	227	230	139	98	102	104	207
alk	-26	-24	-26	-30	-27	-56	-57	3	6	4	14	27
A-								6	7	6	6	13

Naustdal soil summary
Depths: A. Stuanes Means: J. Reuss Table 3

Horizon means	Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
O	12	196	431	36.2	22.5	3.6	5.8	68.1
E	5	886	29	13.4	8.6	6.9	4.3	33.2
B	31	760	67	5.9	2.9	3.4	2.0	14.2
C,BC	25	1037	38	6.0	2.0	4.4	2.2	14.5
IIC	3	1431	15	10.3	3.3	8.4	3.2	25.1
Total mean	75	800	62	7.9	3.6	4.4	2.4	18.4

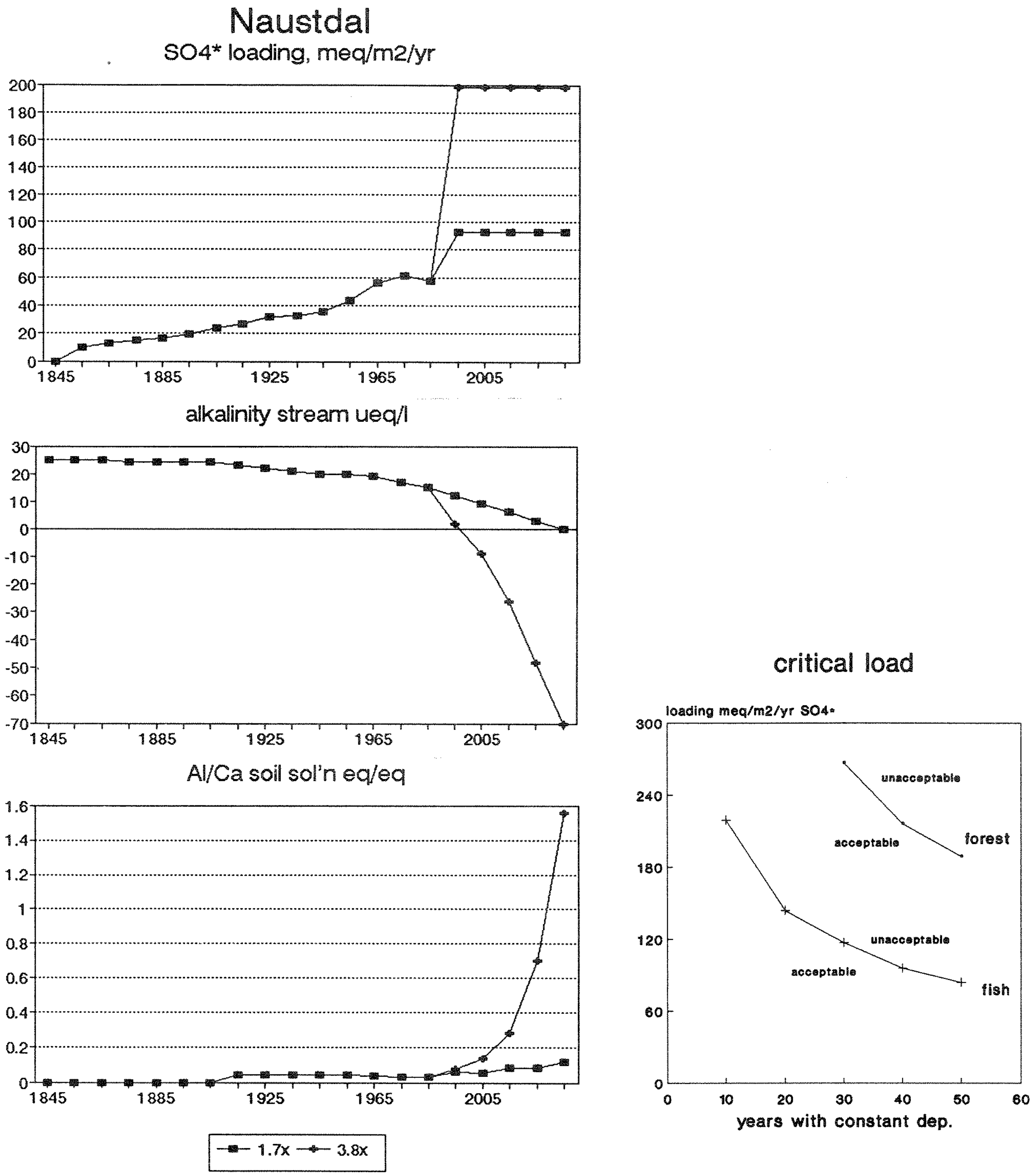


Figure 8. Naustdal. (See text to Figure 2)

is 3.8x. Again these calculations assume that nitrogen uptake in the catchment occurs at present-day rates; if nitrogen leaching increases, then the critical load for sulfur must be decreased accordingly.

4.8 Risdalsheia

Input-output data for Risdalsheia are for the reference catchment ROLF (no roof, acid precipitation) for the 3-year period 1985-87 (Wright et al. 1988) (Table 11). Soil parameters necessary for the MAGIC model are derived by Reuss (1989) based on data from Lotse (1989) (Table 11).

Sulfur deposition at Risdalsheia is about 101 meq/m^2/yr (Figure 9) and far exceeds the critical load for fish (7 meq/m^2/yr from MAGIC, -10 meq/m^2/yr from the empirical model) because alkalinity in runoff is -80 μeq/l. MAGIC application indicates that the current Al/Ca ratio in soil solution is about 2.4 which suggests that the current loading also exceeds the critical load with respect to forest (60 meq/m^2/yr).

The critical load calculated by the empirical model is actually negative; this implies that unless nitrate concentrations in runoff are reduced as well, a 100% reduction in sulfur loading is insufficient to give positive alkalinity.

The MAGIC estimates indicate that the loading of non-marine sulfate must be reduced by about 40% to 65 meq/m^2/yr to meet the forest criterion, and a full 90% to about 10 meq/m^2/yr to meet the fish criterion (Figure 9).

4.9 Sogndal

Input-output data for Sogndal are the averages from the two reference catchments SOG1 and SOG3 for the 4-year period 1984-87 (Wright et al. 1988) (Table 12). Soil parameters necessary for the MAGIC model are derived by Reuss (1989) based on data from Lotse (1989) (Table 12).

Table 11. Risdalsheia. Upper panel: input-output data used to calibrate the MAGIC model. Data from Wright et al. (1988). Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. Lower panel: soils data used to calibrate the MAGIC model. Data from Lotse (1989) and Reuss (1989).

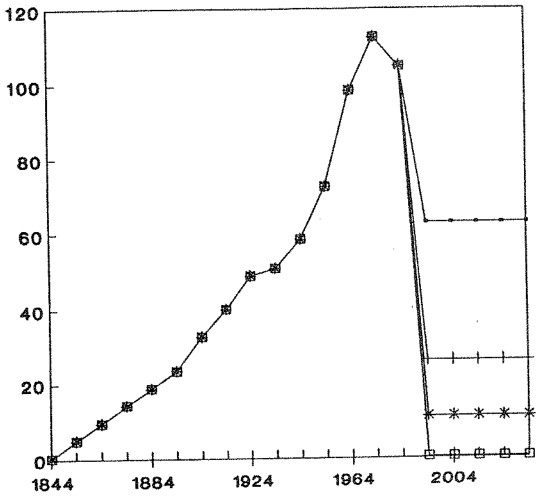
	Input concentration ueq/l				Flux		Output concentration ueq/l				Flux
Yr.	1985	1986	1987	mean	meq/m2	Cl-korr	1985	1986	1987	mean	meq/m2
H2O	1409	1516	1524	1483	1483	1673	999	1388	1324	1237	1237
H+	72	77	63	71	105	118	87	93	70	83	103
Na	56	102	60	73	108	122	84	101	85	90	111
K	5	5	3	4	6	7	4	4	3	4	5
Ca	8	12	8	9	14	16	15	20	15	17	21
Mg	11	25	17	18	26	30	25	30	21	25	31
Al							8	12	12	11	13
NH4	44	42	36	41	60	68	14	14	6	11	14
SO4	77	87	66	77	114	128	104	108	68	93	115
Cl	56	119	69	81	121	136	92	130	108	110	136
NO3	50	49	40	46	69	78	31	29	14	25	31
HCO3											
SBC	124	186	124	145	215	242	142	169	130	147	182
SAA	183	255	175	204	303	342	227	267	190	228	282
alk	-59	-69	-51	-60	-88	-100	-85	-98	-60	-81	-100
A-							10	7	22	13	16

Risdalsheia soil summary
Means: Reuss (1989) Table 5.1, p. 46

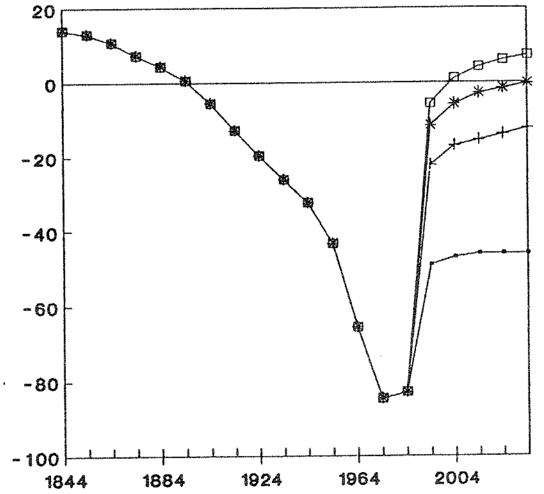
Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
0-15	221	139	11.2	5.9	1.4	2.8	21.3
15-30	630	64	3.5	1.9	1.4	1.6	8.4
30-45	656	47	3.2	1.7	1.4	1.3	7.6
>45	637	58	3.3	1.8	1.4	1.5	8.0
total	401	82	5.4	2.8	1.4	1.9	11.5

Risdalsheia

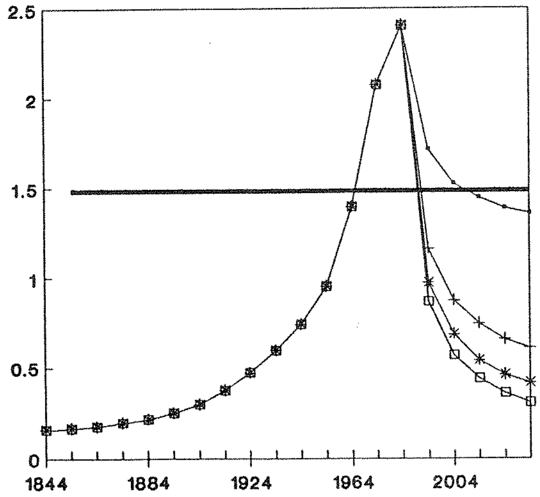
SO4* loading, meq/m2/yr



alkalinity stream, ueq/l



Al/Ca soil sol'n eq/eq



critical load

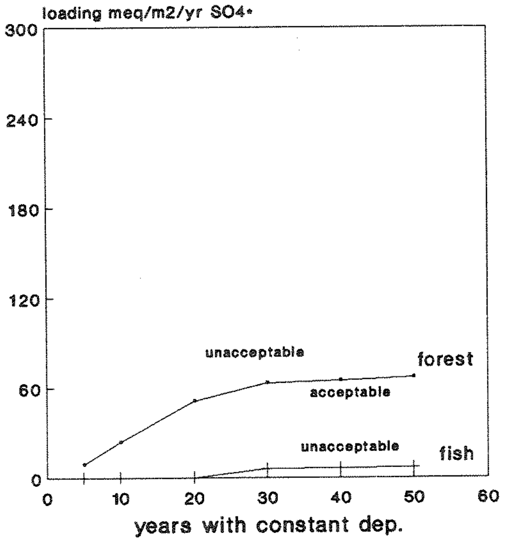


Figure 9. Risdalsheia. (See text to Figure 2)

Table 12. Sogndal. Upper panel: input-output data used to calibrate the MAGIC model. Data from Wright et al. (1988). Units: flux meq/m^2/yr, concentrations μeq/l, H_2O mm/yr. Lower panel: soils data used to calibrate the MAGIC model. Data from Lotse (1989) and Reuss (1989).

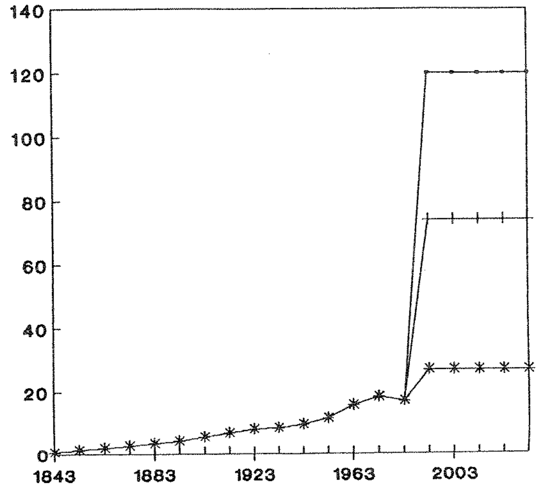
	Input concentrations ueq/l					Flux		Output concentrations ueq/l					Flux
Yr.	1984	1985	1986	1987	mean	meq/m2	Cl-korr	1984	1985	1986	1987	mean	meq/m2
H2O	1126	928	957	925	984	984	940	1026	828	857	790	875	875
H+	20	15	11	18	16	16	15	3	2	1	2	2	2
Na	72	32	22	28	39	38	36	81	34	32	38	46	40
K	6	4	6	6	6	5	5	6	2	1	2	3	2
Ca	9	4	3	6	6	5	5	20	16	18	20	19	16
Mg	16	4	5	5	8	7	7	16	8	8	10	11	9
Al								0	0	0	0	0	0
NH4	9	6	7	14	9	9	8	3	2			3	2
SO4	31	16	20	24	23	22	21	26	22	25	22	24	21
Cl	81	26	25	30	41	40	38	84	26	28	36	44	38
NO3	9	8	5	11	8	8	8	2	0	1	0	1	1
HCO3								8	9	4	10	8	7
SBC	112	50	43	59	66	65	62	126	62	59	70	79	70
SAA	121	50	50	65	72	70	67	120	57	58	68	76	60
alk	-9	0	-7	-6	-6	-5	-5	6	5	1	2	4	11
A-								9	7	2	4	7	6

Risdalsheia soil summary
Means: Reuss (1989) Table 5.1, p. 18

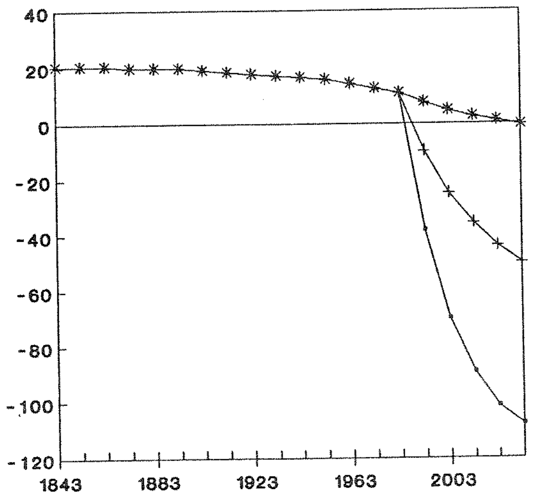
Depth cm	Density g/l	CEC mmol/kg	Ca %	Mg %	Na %	K %	BS %
0-15	511	55	18.3	4.9	2.0	3.0	28.2
>15	738	22	16.8	3.1	2.0	3.0	24.9
total	618	37	17.5	3.9	2.0	3.0	26.4

Sogndal

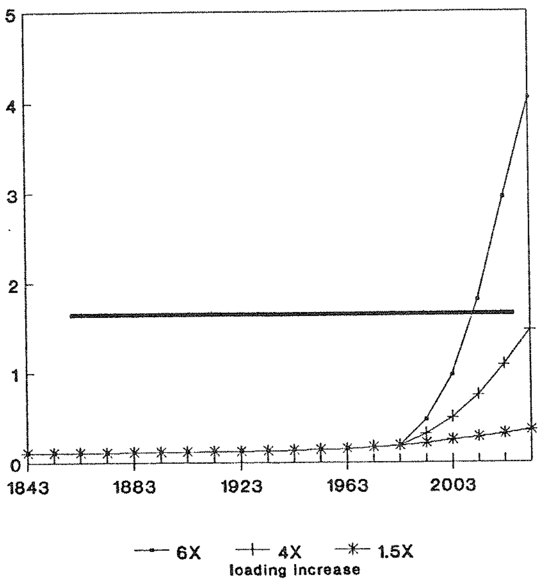
SO4* loading, meq/m2/yr



alkalinity stream ueq/l



Al/Ca soil sol'n eq/eq



critical load

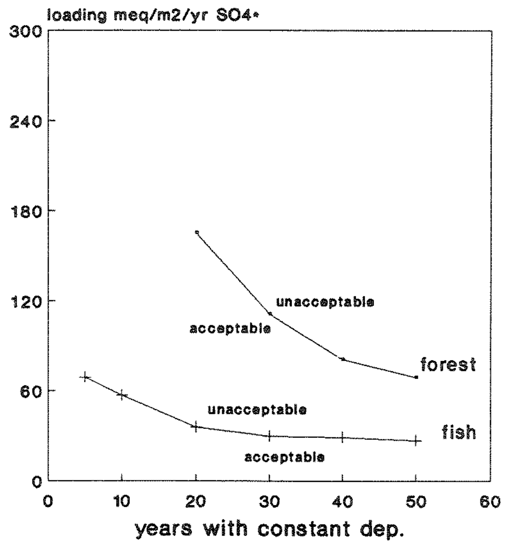


Figure 10. Sogndal. (See text to Figure 2)

At Sogndal current levels of sulfur deposition (17 meq/m^2/yr) lie below the critical load; streamwater has positive alkalinity and the MAGIC application indicates a current Al/Ca ratio in soil solution of about 0.3 (Figure 10). Here MAGIC indicates that the critical load is about 27 meq/m^2/yr using the fish criterion and 74 meq/m^2/yr using the forest criterion. The empirical model gives a critical load for fish of 21 meq/m^2/yr.

5. Discussion

5.1 Fish vs. forest

For all the sites investigated the fish criterion is the more stringent. If the fish criterion is met, then the Al/Ca ratio in soil solution will be satisfactory. This is true regardless by which method the critical load is calculated (Figure 11).

For these 9 sites the critical load for soil calculated by MAGIC using the forest criterion is proportional to the critical load for soil using the fish criterion (Figure 12). The least-squares regression of critical load (forest) on critical load (fish) is $y = 60 + 1.5\ x$, with $r^2 = 0.7$, $n = 9$. The relationship is approximately the same using as independent variable critical load (fish) determined by either the empirical model or the long-term steady-state value (Figure 12).

This relationship between critical load for soils using the forest criterion and using the fish criterion is not unexpected in that both are basically related to the inherent sensitivity of the soils in the various catchments. Thus capacity factors as soil thickness, bulk density, cation exchange capacity, and base saturation combined with flux factors such as weathering rate and base cation deposition together determine the critical load for soil regardless of criterion used. For these 9 sites the regression analyses indicate that the static empirical model can thus be used to estimate the critical load for soils for the forest criterion. This in turn implies that present-day water chemistry data are sufficient to estimate critical loads for soils. Since all the sites treated here are characterized by thin and

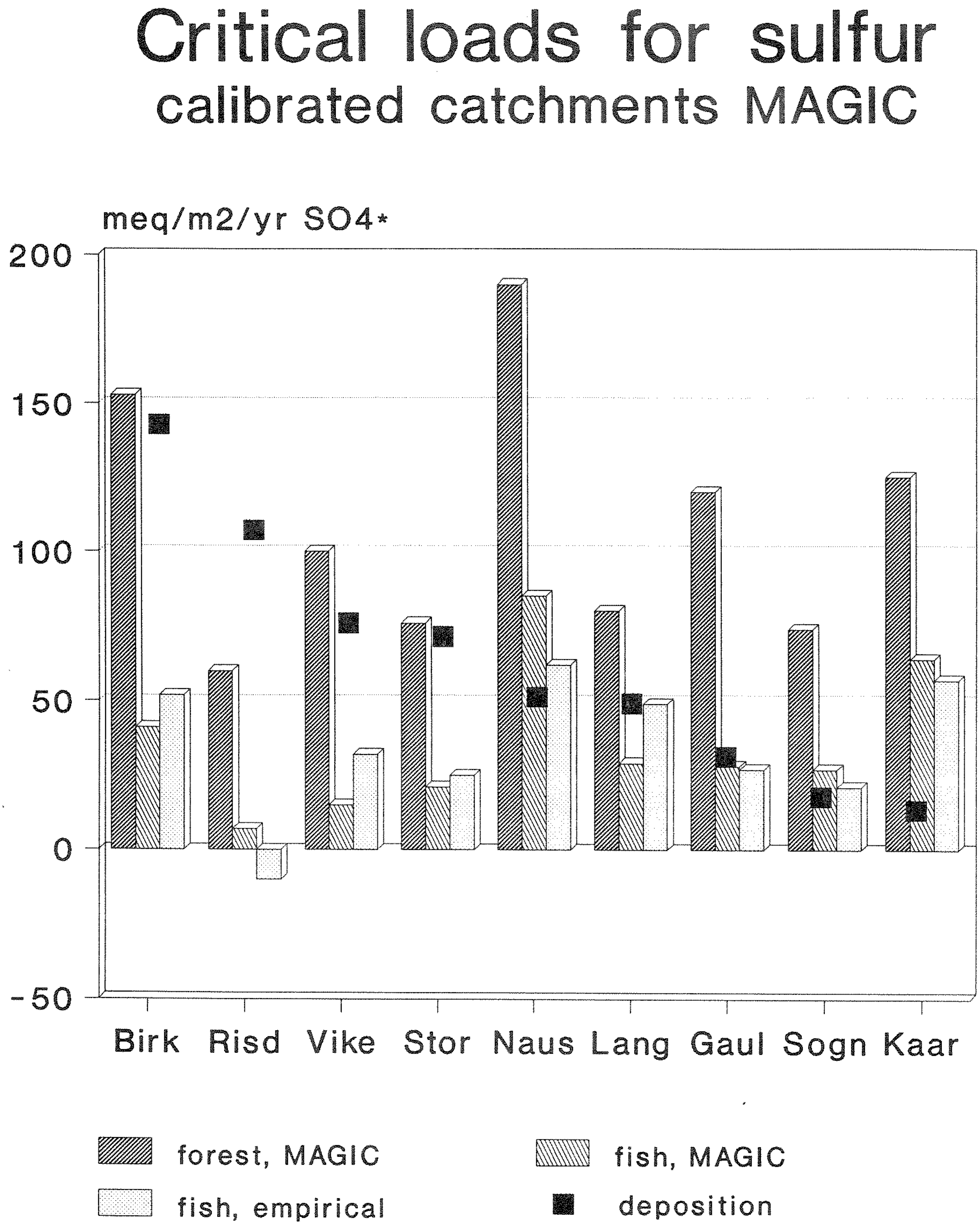


Figure 11. Critical loads for non-marine sulfur at 9 calibrated catchments in Norway. Three estimates of critical load for soils are shown; the dynamic MAGIC model using (1) the forest criterion (Al/Ca in soil solution = 1.5 eq/eq) and (2) the fish criterion (alkalinity in runoff = 0), and (3) the static empirical model using the fish criterion. Also shown is present-day sulfur deposition (1 g S/m^2/yr = 60 meq/m^2/yr).

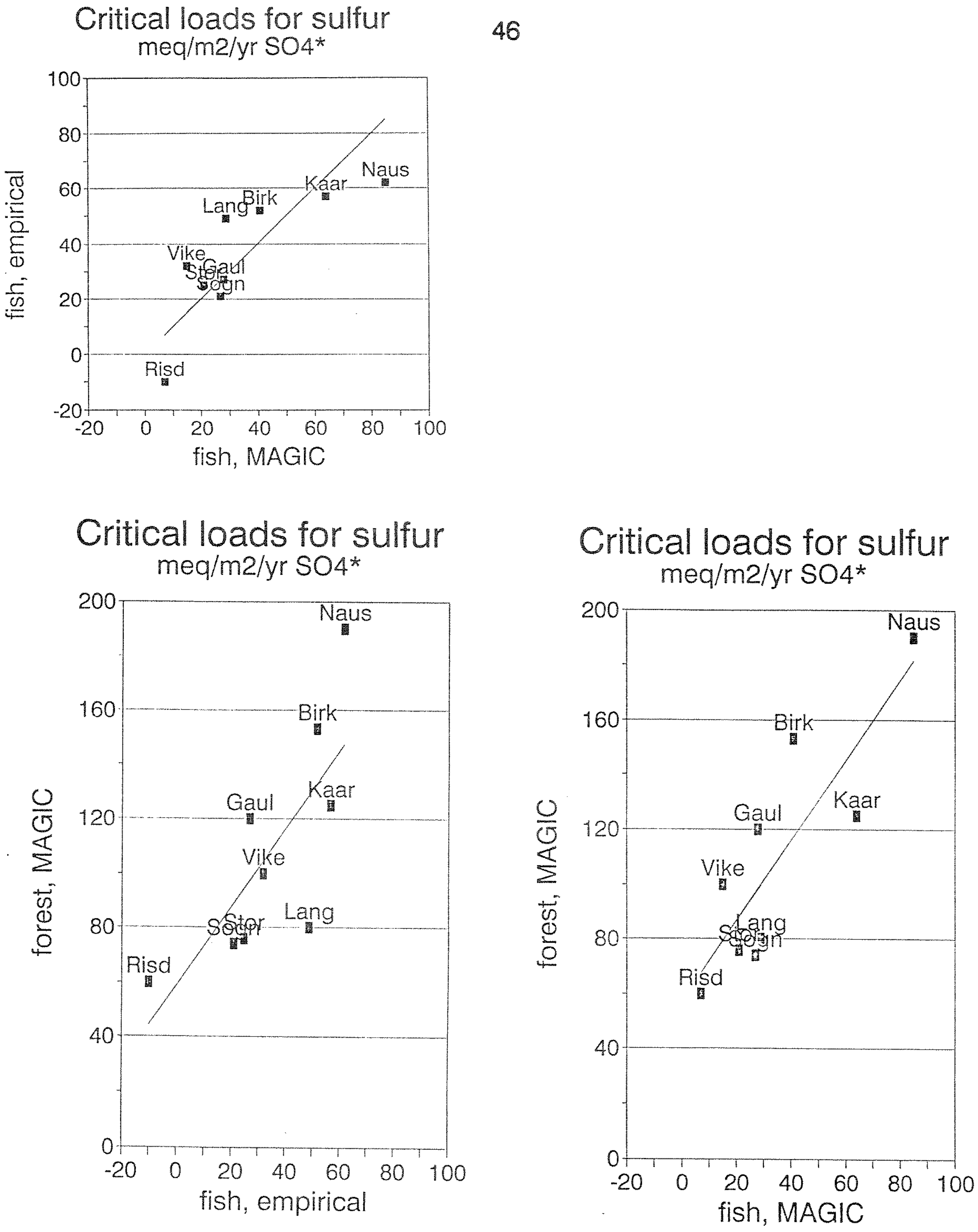


Figure 12. Relationships between critical loads for sulfur estimated by the dynamic MAGIC model (situation after 50 years of changed deposition) using the forest and fish criteria and the static empirical model using the fish criterion. Top left panel: MAGIC (forest) vs. MAGIC (fish). The forest criterion is less stringent by about a factor of 2 (least-squares regression line shown $Y = 57 + 1.46 X$, $r^2 = 0.72$, $p < 0.01$). Top right panel: MAGIC (forest) vs. empirical (fish). Least-squares regression line shown $Y = 59 + 1.43 X$, $r^2 = 0.57$, $p < 0.05$. Bottom left panel: empirical (fish) vs. MAGIC (fish). The correlation coefficient r^2 is 0.66, $p < 0.05$. Shown is the 1:1 line.

patchy soils, however, estimates for critical load obtained from these regressions should be restricted to other such areas. Much of Norway has this type of soil.

For areas with soil thickness exceeding 50 cm, quite different relationships may exist between the cortical load for soils with respect to forests and with respect to fish. Coniferous trees such as Norway spruce are shallow rooting; generally only the situation of the upper soil (0-50 cm) is of interest. Yet surface waters may derive from runoff that has percolated though deeper soil layers and interacted with a much larger volume of soil. Under such situations the soil solution in the upper horizons may been highly acidic and the Al/Ca ratio exceed the critical level of 1.5 μeq/μeq while groundwater and surface waters may still have alkalinity > 0. The methods used here on the 9 catchments should also be tested at sites with thicker soils. The research site at Nordmoen operated by NISK is a potential such site.

5.2 Time-variability of critical load

Each site has its inherent sensitivity to acid deposition. For the fish criterion of alkalinity > 0 the long-term steady-state critical load for a given site is equal to the sum of weathering rates and deposition inputs of excess base cations. Deposition of excess base cations can be measured or estimated directly; the problem lies in the determination of weathering rates for entire catchments, or entire regions in the case of mapping.

The several methods for determining critical loads proposed in the UN-ECE handbook in fact indirectly or directly entail alternative techniques for estimation of weathering rates, either from present-day water chemistry, soil mineralogy, or a combination of soil and water chemistry.

The base cations stored in the soil represent a large sink for acid due to the process of cation exchange. A given site may tolerate decades to centuries of sulfur deposition at rates well above the inherent long-term steady-state critical load. Thus the critical load for a given site is not constant over time, but depends on the history of acid deposition at the site. The MAGIC model as used here illustrates the time-dependent variability of the critical load.

The critical load depends on the length of time during which the catchment is allowed to adjust to a new loading of sulfur. For catchments at which present-day deposition has not pushed the stream alkalinity below zero or the Al/Ca ratio in soil solution above 1.5, the longer the adjustment time, the lower the critical load. The soils acidify slowly in response to acid deposition and thus the alkalinity of streamwater decreases over time. Sogndal provides a good example here (Figure 10).

The RAIN project experiment at Sogndal actually provides a direct test of the time-dependence of critical load. This experiment entails addition of 100 meq $SO_4/m^2/yr$ of sulfuric acid to the small catchment SOG2. This dose is in addition to the ambient loading of 17 meq $SO_4/m^2/yr$. The total of 117 meq $SO_4/m^2/yr$ exceeds by about a factor of 4 the 50-year critical load (fish) of 27 meq $SO_4/m^2/yr$ as estimated by MAGIC. Also the 5-year critical load of 60 meq $SO_4/m^2/yr$ is exceed by a factor of 1.8. The experimental results show that the runoff from this catchment indeed has been acidified after 5 years of treatment such that the volume-weighted mean alkalinity now is below 0 (Wright et al. 1988). The experiment confirms the estimates of critical load for sulfur and the time-variability of the critical load as estimated by the MAGIC model (Wright et al. 1990).

For catchments at which present-day deposition currently exceeds the critical load (alkalinity < 0 or Al/Ca > 1.5), the longer the adjustment time, the higher the critical load. This is because when acid deposition loading is decreased sufficiently, the base saturation in the soils can be gradually replenished by weathering and thus the alkalinity of streamwater increases over time. Birkenes provides a good example here (Figure 2).

The long-term steady-state critical load (fish criterion) for Birkenes is 58 meq SO_4/m^2yr (excess base cations in deposition measured, weathering rate determined from MAGIC) (Table 2). The empirical model gives a critical load of 52 meq SO_4/m^2yr based on present-day water chemistry. The time variability derived from the MAGIC model shows that to obtain alkalinity > 0 within 10 years the critical load is only 12 meq SO_4/m^2yr, whereas after 50 years it is 41 meq SO_4/m^2yr and after 100 years 45 meq SO_4/m^2yr. The value asymptotically approaches the steady-state value of 58 meq SO_4/m^2yr (Figure 13).

If, however, the starting point is not present-day acidified state, but the pre-acidification condition prevailing in, say, 1845, the situation is different. The empirical model gives a critical load of 59 meq SO_4/m^2yr based on MAGIC reconstructed water chemistry, not greatly different than the estimate based on present-day water chemistry. But in the pre-acidification condition Birkenes could tolerate much higher loadings, at least for several decades. The MAGIC model shows that to obtain alkalinity > 0 within 10 years the critical load was 270 meq SO_4/m^2yr, whereas after 50 years of constant deposition 102 meq SO_4/m^2yr and after 100 years 74 meq SO_4/m^2yr. The value asymptotically approaches the steady-state value of 58 meq SO_4/m^2yr and at a much faster rate than under the recovery situation (Figure 13).

5.3 Evaluation of other criteria for forest effects

The UN-ECE Manual (Sverdrup et al. 1989) suggests several soil criteria in addition to the Al/Ca ratio in soil solution for adverse effects to forests due to sulfur deposition. These all refer to the situtation in the upper 0-50 cm of soil (assumed rooting zone) and coniferous tree species.

These additional criteria include soil pH (> pH4.0-4.2), alkalinity (> -200 μeq/l), total aluminium (< 2 mg/l), labile aluminium (<1 mg/l), Mg/Al (>0.2 molar/molar), NH_4/K (<5 molar/molar), Mg-saturation (>0.3%), and base saturation (>1%). All these parameters can be calculated from MAGIC.

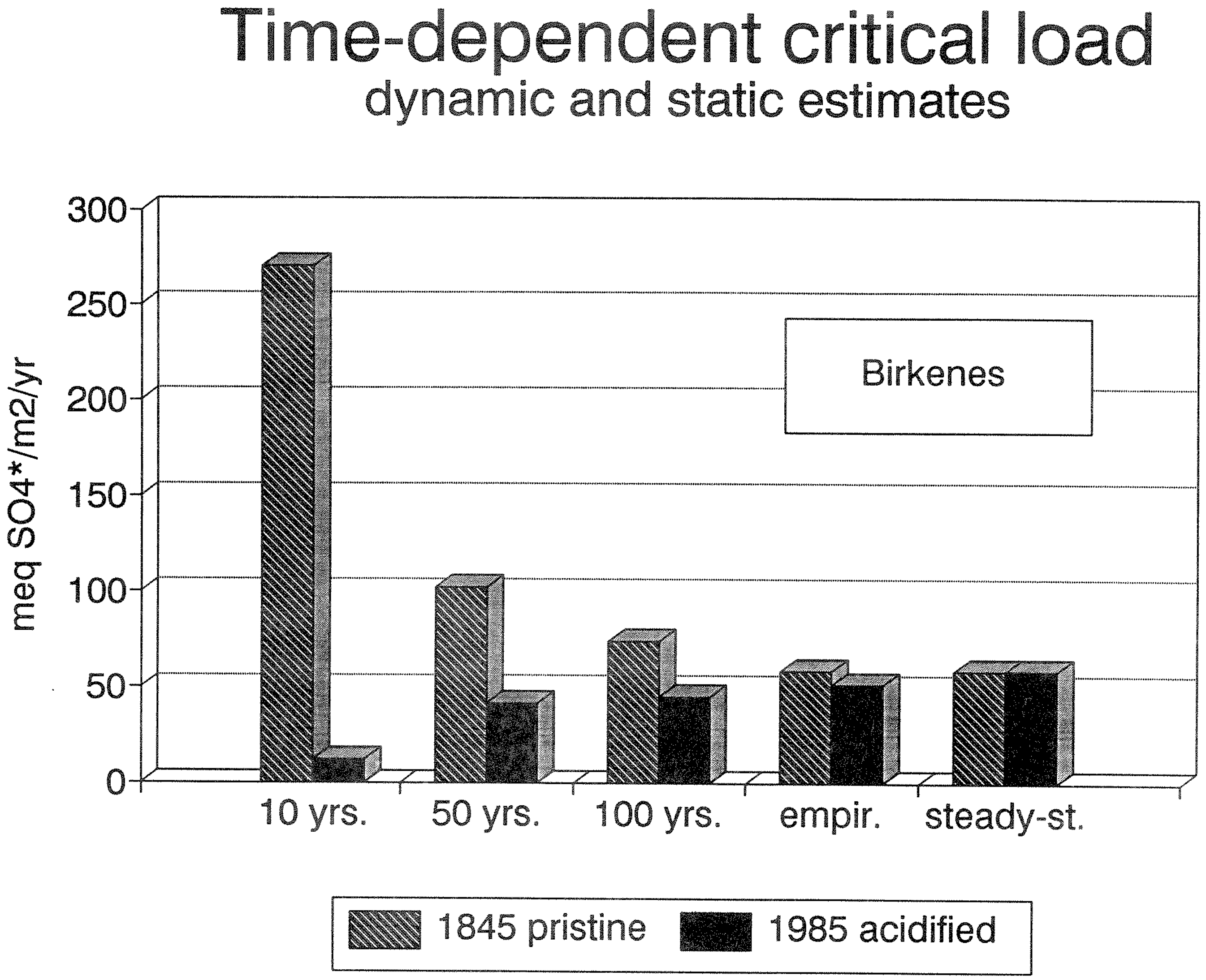


Figure 13. Time dependence of the critical load for sulfur at Birkenes as estimated by the dynamic MAGIC model and the fish criterion. If the starting point is the pre-acidification condition prevailing at 1845, the critical load decreases with the number of years of constant sulfur deposition. If the starting point is the acidified condition of 1985, the critical load increases with the number of years of constant sulfur deposition. In both cases the values converge to the long-term steady-state value which is the sum of weathering and base cation deposition. The empirical estimate is in both cases close to the long-term steady-state value.

For all the 9 catchments investigated here, none of these additional criteria are more stringent than the Al/Ca ratio in soil solution. For Birkenes, for example, at the critical load based on Al/Ca ratio values for all these other criteria are still acceptable for forests (Table 13).

5.4 Nitrogen

All of the estimates of critical loads for sulfur presented here are based on the assumption that the fraction of incoming nitrogen retained in the catchments remains constant. Nitrogen deposition, of course, has increased along with sulfur deposition over the past decades. The calculations and models simply assume that uptake and retention has been proportional to deposition. The predictions for the future also make this assumption.

Table 13. Forest soil criteria for determining critical load as suggested by the UN-ECE draft manual (from Sverdrup et al. 1989). At Birkenes the critical load for sulfur of 153 meq $SO_4/m^2/yr$ that meets the Ca/Al criterion also meets all the other criteria.

Parameter	Units	Criterion	Birkenes Year 2038
pH		>4.0-4.2	4.3
alkalinity	µeq/l	>-200	-90
total Al	mg/l	<2-4	1.5
labile Al	mg/l	<1-2	0.9
Ca:Al molar ratio		>0.5-1.0	1.0
Mg:Al molar ratio		>0.2	0.6
NH_4:K molar ratio		>5	0.2
Mg saturation	%	>0.3	1.0
base saturation	%	>1.0	5.8

There is widespread evidence from southernmost Norway, however, that suggests that an increasing fraction of the incoming nitrogen is leached though the terrestrial ecosystems and lost to streams and lakes (Henriksen and Brakke 1988b, Henriksen et al. 1988). The catchments are retaining a smaller fraction of incoming nitrogen.

Thus for the acidified catchments at which the critical load is exceeded today, the estimates of critical load for sulfur may be too high. In the future a portion of the "tolerable" sulfur deposition may be taken up by nitrogen deposition and leaching. Further analysis of these data should include various plausible "nitrogen saturation" scenarios and derive estimates of critical loads for sulfur alone, nitrogen alone, and the combination of sulfur plus nitrogen. Both the empirical model and the MAGIC model offer ready tools for this purpose.

6. Recommendations for further work

The methods used here on the 9 catchments should also be tested at sites with thicker soils. The research site at Nordmoen operated by NISK is such a potential site. The two-layer version of MAGIC provides a suitable tool.

Further analysis of these data should include various plausible "nitrogen saturation" scenario and derive estimates of critical loads for sulfur alone, nitrogen alone, and the combination of sulfur plus nitrogen. Both the empirical model and the MAGIC model offer ready tools for this purpose.

7. Conclusions

Several conclusions can be drawn from these results regarding estimation of critical loads.

1. For areas with thin soils such as typical for large areas of Norway, the critical load for soils derived from the criterion that surface water alkalinity > 0 (fish

criterion) is substantially lower than the critical load for soils derived from the criterion that Al/Ca equivalent ratio in soil solution not exceed 1.5 (forest criterion). Thus if the critical load for an area is to be set such that both fish and forest are to be protected (restored) then the water criterion is the more stringent by about a factor of 2.

2. The critical load has a time-dependent aspect due to soil acidification. As the soils acidify due to acid deposition, the critical load decreases. Conversely as soils are restored when acid deposition is reduced, the critical load gradually increases. These changes in critical load are on the order of decades. Dynamic models are necessary to assess the time-dependence.

3. For time periods greater than about 30 years the critical load estimated by the dynamic MAGIC model and the empirical model produce similar estimates based on the fish criterion (surface water alkalinity > 0).

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