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NATURENS
TÅLEGRENSER

Miljøverndepartementet

FAGRAPPORT NR. 17

Critical loads for soils in Norway

Nordmoen

Norwegian Institute for Water Research NIVA

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 Grensoverskidende Luft-foruresninger (Genève-konvensjonen). I arbeidet under Genève-konvensjonen er det vedtatt at kritiske belastningsgrenser skal legges til grunn ved utarbeidelse av nye avtaler om utslippsbegrening av svovel, nitrogen og hydrokarboner.

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Abstract: **We evaluate the critical load for soil and water at Nordmoen using the dynamic model MAGIC, the static PROFILE model, and the empirical method as suggested by the mapping handbook. Nordmoen is located about 60 km N of Oslo on thick deposits of glaciofluvial sands, and receives moderate (for Norway) levels of acid deposition (53 meqSO_4/m^2/yr). At Nordmoen both acid deposition and forestry practices have caused soil acidification.**

MAGIC indicates that the "tolerable" load is 0 meq SO_4/m^2/yr under the conditions that the Ca/Al molar ratio in soil solution be above 1 or 0.5 . This estimate assumes that forestry practices will continue for the next 50 years. The empirical method for waters gives a critical load estimate of 126 meq SO_4/m^2/yr.

Nordmoen is thus a site in Norway at which the soil and forest are more sensitive than surface waters. These results can be used to determine under which circumstances forest will be more sensitive than fish, and thus provide a basis for mapping critical load.

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Critical Loads for Soils in Norway

Nordmoen

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Contents

Norsk sammendrag

Nedfall av forsurende svovel- og nitrogenforbindelser fører til gradvis forsuring av vann og jord. Disse endringer vil så kunne få effekt på fisk og skog. Det er en stor nasjonal og internasjonal aktivitet for å redusere utslippene av forurensende stoffer. En del av disse bestrebelsene er arbeidet med å bestemme tålegrenser for økosystemene.

Tålegrensen er blitt definert som den høyeste belastning av forsurende komponenter som ikke vil gi skadelige effekter på økosystemenes struktur og funksjon. Kriteriene for "uakseptable endringer" må sees i forhold til effekter på terrestriske og akvatiske organismer. 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. Det mest brukte tålegrensekriteriet for jord i relasjon til skog er forholdet Ca/Al og for vann i relasjon til fisk at alkaliniteten er større enn null.

I områder med tynnt og usammenhengende jorddekke slik vi finner det i store deler av Norge, vil alkalinitetskriteriet være det strengeste. I en tidligere undersøkelse i 9 nedbørfelt er det vist at tålegrensen for skog er omtrent dobbelt så høy som den for fisk. I områder med tykkere jorddekke kan det forventes at tålegrensen for skog er den strengeste. For å teste dette ble et 40-årig granbestand på Nordmoen nord for Oslo valgt. I dette området er mengden av løsmasser over fjell ca. 60 m. Fra tidligere intensive studier i dette området finnes de nødvendige data for å kjøre de aktuelle modeller for å beregne tålegrensene.

Til beregningene ble den prosess-orienterte og dymaniske MAGIC-modellen sammen med den statiske PROFILE-modellen benyttet. MAGIC kan konstruere forsuringshistorien og predikere framtidig forsuring i tidsperioder på 10-år og 100-år. Modellen benytter gjennomsnittsparametre på nedbørfeltnivå. I modellen fokuseres det på jordkjemiske endringer på grunn av atmosfærisk deposisjon, kjemisk forvitring, opptak i vegetasjonen og utvasking. De jordkjemiske prosessene som inngår i MAGIC er sulfatadsorpsjon, kationbytte, CO_2-reaksjoner, utfelling og oppløsning av aluminium og dissosiering av organiske syrer.

Ved anvendelse av MAGIC-modellen på data fra Nordmoen ble det kjørt en optimaliseringsprosedyre for å bestemme den opprinnelige metningen og forvitringen av de fire basekationene i 1848. Modellen ble så kjørt for 140-års perioden fram til 1988 slik at den passet best mulig med dagens målte verdier for jordkjemi og jordvann. Tålegrensene ble så beregnet under forutsetning av at belastningen brått ble endret til et nytt nivå og holdt konstant i 50 år. MAGIC ble så kjørt gjentatte ganger med ulike nivåer av nedfall inntil kriteriene for alkalinitet på henholdsvis 0, 20 og 50 μekv./l (fisk) eller Ca/Al på 1.0 og 0.5 mol/mol (skog) ble nådd. De tålegrenser som er beregnet gjelder svovel og det er forutsatt at belastning og igjenholdelse av nitrogenforbindelser ikke endres.

Ved bruk av PROFILE-modellen beregnes forvitringen og dermed dagens tålegrense for et jordprofil med flere sjikt. Nøkkelparametre er tekstur og mineralogi. For Nordmoen ble alle 5 definerte sjikt ned til 60 cm benyttet.

Tålegrensen for vann (fisk) ble beregnet ved bruk av Henriksens empirisk vannmodell. Denne modellen er basert på dagens vann- og nedbørskjemi. Modellen er statisk på den måten at den spesifiserer den vannkjemien som skapes av en gitt endring i deposisjonen, uten å spesifisere hvor lenge denne vannkvaliteten vil bestå.

Som inngangsdata ble benyttet data for perioden oktober 1986 til september 1988. Disse inkluderer nedfall, kronedrypp, strøfall, jordvann, fysiske og kjemiske forhold i jorda og beregnet netto næringsopptak i trærne i tillegg til grunnvannsdata for vannmodellen. Rotdybden i bestandet er ca. 60 cm og jordvann oppsamlet i denne dybden ble tatt som et mål på mengden av elementer som gikk tapt fra skog-jord-systemet.

Utviklingen i nedfallet av forurensningskomponenter på Nordmoen ble antatt å ha vært som i Europa forøvrig. Det er videre antatt at det har vært mer og mindre plukkhogst i skogen fram til flatehogst i 1947. Etter denne hogsten ble det plantet gran. Netto-opptaket av næringsstoffer ble antatt å være null fram til bruken av skogen startet, men med gradvis økende netto-opptak med økende uttak av tømmer. Netto-opptaket gikk brått ned til null ved faltehogsten i 1947 med en påfølgende rask stigning til dagens nivå.

MAGIC-beregningene viser at basemetningen på Nordmoen har gått ned fra 36% i 1848 til 11% i 1988. Utviklingen fra 1975 til 1988 stemmer bra med målinger gjort i et nabobestand av omtrent samme alder. MAGIC indikerer at surt nedfall har bidratt med ca. 1/3 og næringsopptaket i skogen med ca. 2/3 til denne forsuringen. Prognosen for de kommende 50 år viser fortsatt jordforsuring på Nordmoen.

Videre beregninger er foretatt etter fire ulike senarier:

1) 40% reduksjon i sulfatdeposisjonen i perioden 1989-2005 og så konstant på dette nivå til 2038 i tillegg til en lineær reduksjon i netto-opptaket på 25% i perioden 1989-2038.
2) 40% reduksjon i sulfatdeposisjonen (som 1) og en brå 100% reduksjon i opptaket i perioden 1989-2038.
3) 90% reduksjon i sulfatdeposisjonen i perioden 1989-2005 og så konstant på dette nivå til 2038 i tillegg til en reduksjon i netto-opptaket på 25% i perioden 1989-2038.
4) 90% reduksjon i sulfatdeposisjonen (som 3) og en brå 100% reduksjon i opptaket i perioden 1989-2038.

En 40% reduksjon i sulfatdeposisjonen er det en kan forvente som reduksjon i Europa. Senariene med 90% reduksjon er tatt med for å illustrere effekten av maksimal reduksjon i utslipp. En gradvis reduksjon i netto-opptaket i skogen på 25% i løpet av de neste 50 år er en sannsynlig utvikling hvis skogen fortsetter å vokse uforstyrret. En brå reduksjon i opptaket på 100% representerer en flatehogst i 1989 med overgang til grasmark.

MAGIC-beregningene viser at også framover vil jordforsuringen påvirkes sterkt av næringsopptaket. Med 100% reduksjon i opptaket vil nedgangen i basemetningsgrad stoppe og en bedring vil starte. Denne vil gå raskere med 90% reduksjon i svoveldeposisjon. Alkaliniteten i jordvannet vil forbedres ved alle senarier med unntak av det første.

Den opprinnelige tålegrensen for skog (1848) var 4,5 til 7 ganger høyere enn dagens svovelbelastning. Dagens tålegrense med Ca/Al forhold på over 1 eller 0.5 vil være 0 mekv. SO_4/m^2/år under forutsetning av dagens belastning og samme skogpraksis som nå i 50 år framover. PROFILE-modellen vil under disse forutsetninger gi en tålegrense på 35 mekv. SO_4/m^2/år. Hvis framtidig næringsopptak stoppes, vil tålegrensen økes til 47 og 105 mekv SO_4/m^2/år for de to Ca/Al-verdiene (MAGIC). Den empiriske vannmodellen gav en tålegrense på 126 mekv. SO_4/m^2/år.

Modellberegningene ved bruk av data fra Nordmoen har vist at det har foregått en betydelig jordforsuring på grunn av opptak av basekationer i biomassen i tillegg til surt nedfall. Hvis Ca/Al forholdet er en god indikator på rotskade, noe det ikke er god nok dokumentasjon på, er det 40-årige granbestandet på Nordmoen i faresonen. Næringssyklusstudiene indikerer at næringsopptaket er stort i forhold til forvitringsbidraget. Disse forhold gjør at det fortsatt vil bli en jordforsuring med nåværende skogpraksis.

Denne undersøkelsen har også vist at på Nordmoen hvor en har mektige løsmasser er tålegrensen for jord lavere enn for grunnvann. Dette resultatet står i sterk kontrast til undersøkelsen fra de tidligere nevnte 9 nedbørfelter med tynnt og usammenhengende jorddekke.

Kartlegging av tålegrenser i Norge bør fokusere på de mest følsomme deler av økosystemene. I områder med liten og usammenhengende jorddekning synes vann å være mer følsom enn jord. I områder med tykke jordmasser som Romerike, deler av Hedmark og Oppland og Finnmarksvidda bør tålegrensearbeidet konsentreres om jord og skog.

Preface

This work was conducted in 1990-91 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 is 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).

This report evaluates the critical load for sulfur with respect to both soils, forest and surface waters at Nordmoen, an intensively-studied research site located about 60 km N of Oslo. The data were collated and evaluated by Arne O. Stuanes, while Richard F. Wright and Tore Frogner conducted the modelling work. We thank NISK for use of unpublished data. This work has profited from helpful discussions with A. Henriksen, T. Sogn and S. Teveldal.

1. Introduction

Deposition of acidic sulfur and nitrogen compounds from the atmosphere (acid deposition) leads to acidification of soils and surface waters, with adverse effects to forests and fish. To attack this problem and to prevent further environmental damage, various national and international organizations in both Europe and North America have taken action to reduce the emissions of acidifying compounds to the atmosphere. At first international agreements such as the UN ECE Conventional on Transboundary Pollutants (the "30% club") were based on reductions of fixed percent in each country. Recently this "across-the-board" approach has been supplanted by the concept of critical loads, in an attempt to reach a more environmentally-sound and cost-effective emissions reduction strategy.

Critical load is defined as "the maximum deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function" (Nilsson and Grennfelt 1988). The "harmful effects" are usually biological, and the criteria are set in relation to terrestrial and aquatic organisms. The critical load for soil is thus set in relation to either terrestrial or aquatic organisms. By itself soil is inanimate and the term "damaged" soil has no meaning. Criteria for soil are thus expressed (1) in relation to damage to vegetation; the ratio of calcium to aluminum in soil solution in the rooting zone (0-50 cm) is the most commonly-used criterion, and (2) in relation to damage to fish; here the criterion is that the water draining the soil should have alkalinity greater than 0 μeq/l (Nilsson and Grennfelt 1988, Sverdrup et al. 1990).

For a given ecosystem the critical load determined with respect to these 2 criteria will differ depending upon the inherent sensitivity of the natural environment. In regions with thin and patchy soils such as are characteristic of large regions of Norway, the 0 alkalinity (fish) criterion is usually the more stringent. An analysis of critical loads for soils at 9 calibrated catchments in Norway showed that the fish criterion was more stringent by at least a factor of 2 (Wright et al. 1990). These sites all have thin and patchy soils.

In regions with thicker soils, however, the forest criterion may be the more stringent, because the surface water will procure additional alkalinity from soil horizons below the rooting zone. To test this hypothesis we evaluate the critical load for soil at Nordmoen, an intensively-studied research site at which the soil and overburden is 60 meters thick. We use the process-oriented dynamic model MAGIC as well as the static PROFILE model and the empirical method as suggested by the mapping handbook (Sverdrup et al. 1990). These results can be used to determine under which circumstances forest will be more sensitive than fish, and thus provide a basis for mapping critical load.

2. The site: Nordmoen

The Nordmoen Field Station is located about 60 km N of Oslo at 200 m elevation (Figure 1). This area receives moderate (for Norway) levels of acid deposition with pH about 4.3 and sulfate deposition about 53 meq/m^2/yr (Table 1).

Table 1. Major ions in deposition (wet+dry), lysimeter water at 60 cm, and groundwater at Nordmoen. Data are averages for 1986-88 (Johnson and Lindberg 1991). Alkalinity (alk) is calculated as difference in sum of base cations (SBC) and sum of strong acid anions (SSA). Units: fluxes in meq/m^2/yr; concentrations in μeq/l.

	deposition		leachate 60 cm		groundwater
	flux	conc.	flux	conc.	conc.
H_2O mm	1110	1110	410	410	N.D.
pH	4.3	4.3	4.9	4.9	5.8
Ca	11	10	16	39	125
Mg	6	5	15	36	51
Na	20	18	35	85	91
K	7	6	4	10	12
NH_4	36	32	0	1	3
Al	0	0	7	18	<10
SO_4	62	56	52	127	162
Cl	22	20	23	55	70
NO_3	42	38	0	1	3
F	N.D.	N.D.	N.D.	N.D.	N.D.
SBC	69	61	61	150	157
SSA	126	114	75	183	235
alk	-57	-53	-14	-33	-78

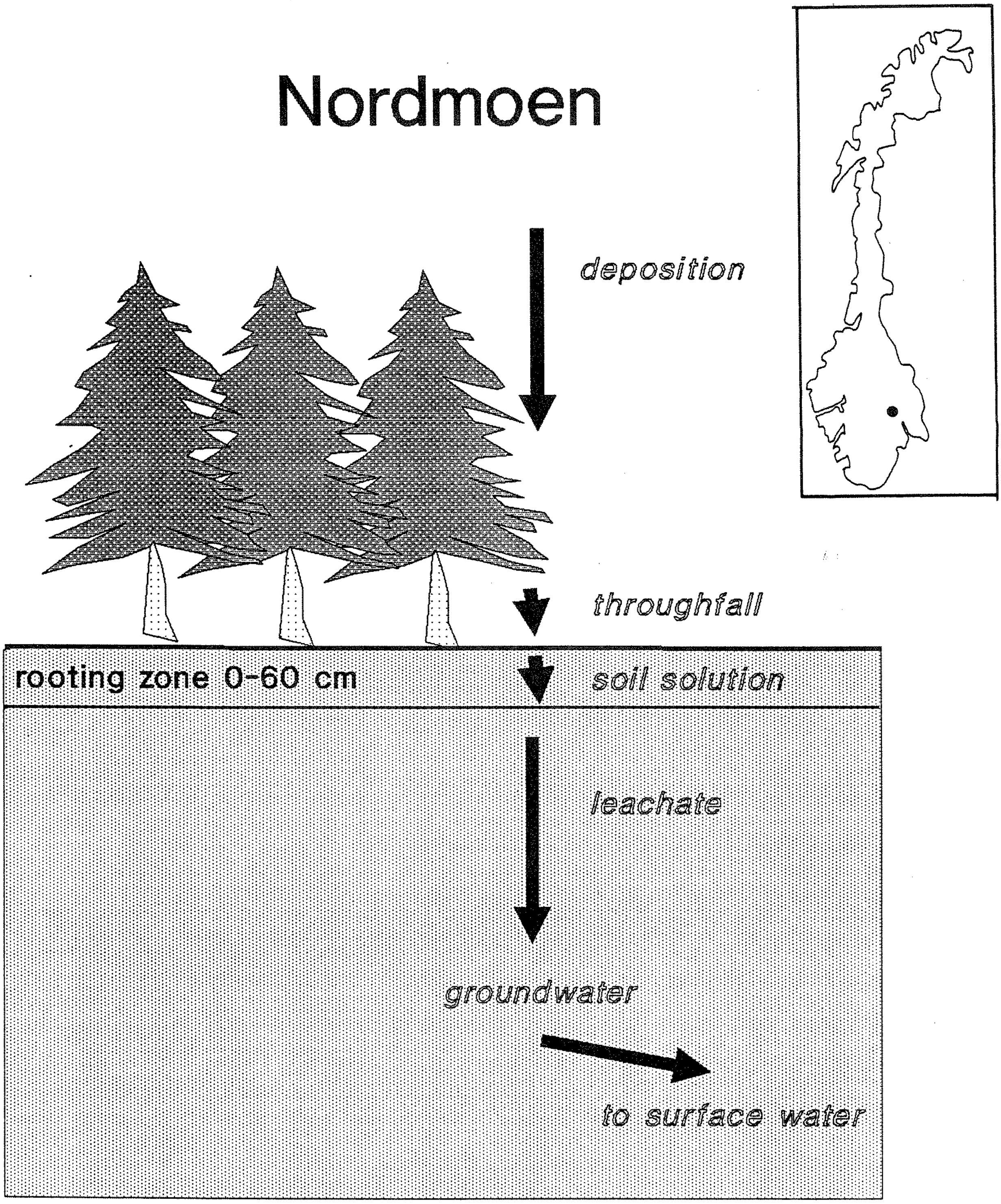


Figure 1. Schematic diagram of flux of water though the forested ecosystem at Nordmoen. Insert: location map. The station is operated by the Norwegian Forest Research Institute (NISK).

The site is located on an extensive flat, glaciofluvial sand plain about 60 m in depth. The groundwater table lies 1-3 m beneath the surface. The sand consists of about 50% quartz, 25% feldspar, and 25% mica and amphibole (Teveldal et al. 1990). The soils are iron and iron-humus podzols developed down to about 60 cm (Table 2). Vegetation is a 40-year second-growth forest of Norway spruce.

Table 2. Soil characteristics at Nordmoen. Data for the individual horizons are weighted by thickness and bulk density and aggregated for the entire 0-60 cm rooting zone. Data from Johnson and Lindberg (1991) or estimated.

Parameter	Units	Value
depth	cm	60
porosity	fraction	0.5
bulk density	kg/m^3	1275
cation exchange capacity	meq/kg	20
SO_4 adsorption, half saturation	meq/m^3	250
SO_4 adsorption, maximum capacity	meq/kg	5.2
log solubility ($AlOH_3$)	---	8.6
dissolved organics	$mmol/m^3$	170
pK_1 organics	---	4.5
pK_2 organics	---	8.0
temperature	°C	4.3
pCO_2 soil air	atm	0.01
Ca saturation	%	5.9
Mg saturation	%	1.4
Na saturation	%	0.7
K saturation	%	2.7
sum = base saturation	%	10.7

For this study of critical load, data collected October 1986 - September 1988 at site R1 as part of the Integrated Forest Study (Johnson and Lindberg 1991) were used. These include 2-year average fluxes of major ions in precipitation, throughfall, and soil solution. Soil physical and chemical parameter were determined by horizon using standard methods. Nutrient uptake by the growing forest was calculated by difference from measurement of throughfall, litterfall, and annual increase of storage in biomass and was set equal to the wood requirement (Table 3).

Table 3. Net nutrient uptake at Nordmoen 1986-1988 calculated from measurement of throughfall, litterfall, and annual increase of storage in biomass. Uptake of nitrogen species was assumed to be 98% of that in deposition. Data from Johnson and Lindberg (1991). Units: meq/m^2/yr.

Ca	30
Mg	11
K	27
SO_4	4

The rooting depth in this stand is about 60 cm, and soil solution collected at 60 cm was taken as a measure of the flux of major ions out of the forest-soil system. Soil solution was collected monthly by means of tension lysimeters supplied with constant suction of 10 kPa. The water flux was calculated under the assumption that the flux of Cl into the system equals the flux of Cl out.

History of acid deposition (H^+, SO_4, NH_4, NO_3) at Nordmoen was assumed to parallel the European emissions of sulfur as reconstructed by Bettleheim and Littler (1979) (Figure 2). The forestry history includes selective cutting during most of the 1800's and 1900's, and clearcutting in 1947 with replanting of Norway spruce. Net uptake of nutrients in the past was related to the age of the forest, assuming no net uptake prior to onset of forest utilization in the early 1800's, a gradually increasing net uptake as the removal of timber increased, and abrupt drop to zero at clearcutting in 1947, and a rapidly increasing rate of uptake to the present-day (Figure 3).

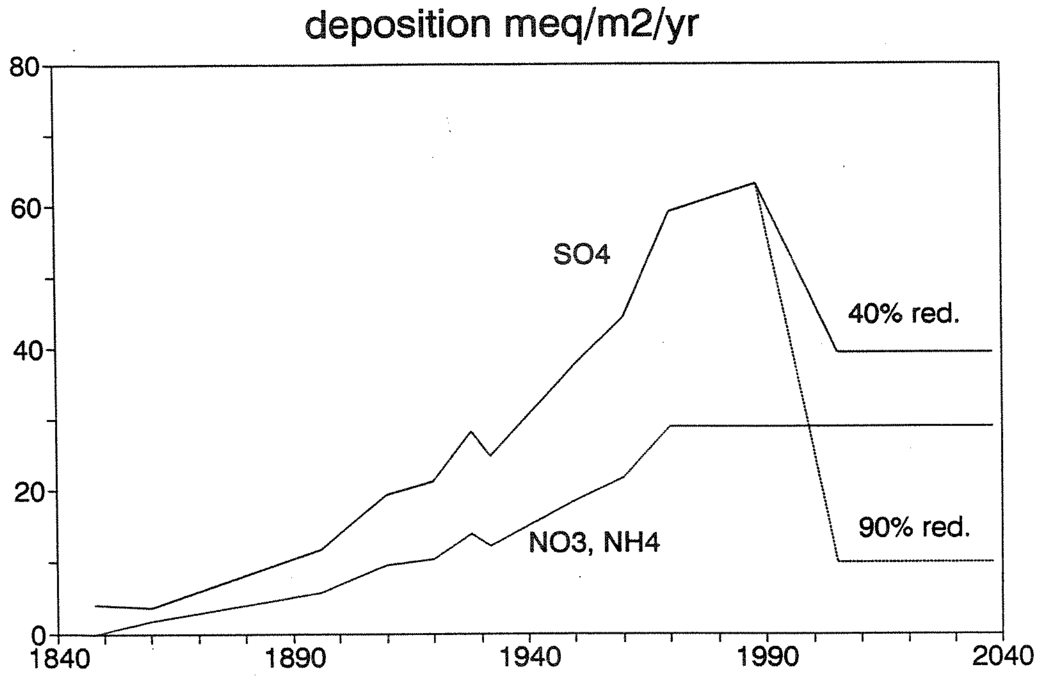


Figure 2. Historical and future acid deposition (wet+dry) at Nordmoen. The present-day levels were measured directly in precipitation and throughfall, and the historical trend was assumed to parallel the emissions of sulfur in Europe as reconstructed by Bettleheim and Littler (1979). For the future 2 scenarios for sulfur deposition were chosen based on a 40% reduction and 90% reduction, respectively.

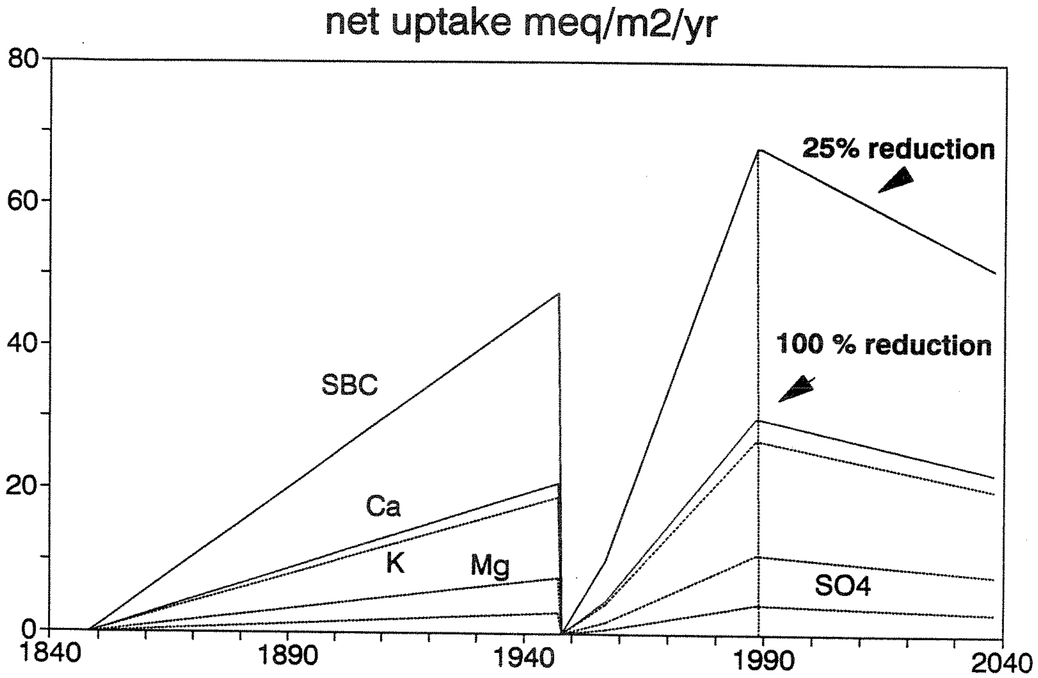


Figure 3. Historical and future nutrient uptake by the forest at Nordmoen. The present-day levels were determined by difference from measurements of precipitation, throughfall, and litterfall. The historical trend was estimated from information regarding forest utilization. The forest was clearcut in 1947 and current stand of Norway spruce planted. For the future 2 scenarios are evaluated, one with continued growth of the existing 40-year-old stand (linear 25% reduction) and one with an abrupt 100% reduction (corresponds to clearcut in 1989 with replanting to grass).

3. The models

3.1 MAGIC

MAGIC (Model for Acidification of Groundwater In Catchments) is a dynamic, 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, chemical weathering, uptake by vegetation, and leaching to runoff (Figure 4). The soil chemical processes in MAGIC include sulfate adsorption, cation exchange, CO_2 dissolution, precipitation and dissolution of aluminum, and dissociation of organic acids.

In the application to Nordmoen here we use an optimization procedure to calibrate MAGIC (Jenkins and Cosby 1989). We use precipitation data, soil and soil solution data together with estimated acid deposition and net uptake histories to produce a calibrated model. 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 1848. This set of initial values when run forward 140 years in time to the present (1988) produces the best fit to the present-day measured soil leachate at 60 cm 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 and uptake 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, 20 and 50 μeq/l (fish) or Ca/Al = 1.0 and 0.5 mol/mol (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.

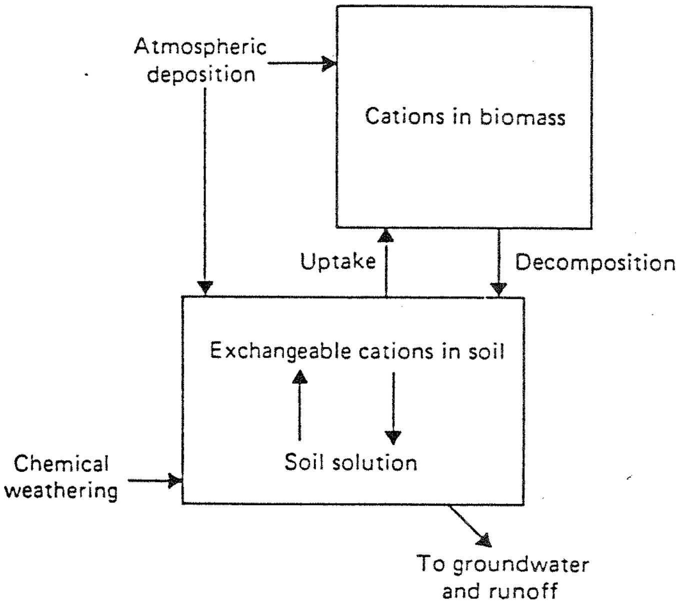


Figure 4. Schematic diagram of structure of the MAGIC model.

3.2 PROFILE

PROFILE is a static model by which the weathering rate and hence the steady-state critical load is calculated for a multi-layered soil profile (Sverdrup and Warfvinge 1988, Sverdrup et al. 1990). Key parameters for the model are soil texture and mineralogy. For Nordmoen we use 5 soil layers (corresponding to the O_i, O_{e+a}, E, B_s, C and IIC horizons) from 0-60 cm depth.

3.3 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. As input data for Nordmoen we use chemical analyses for groundwater (average concentrations of 3 samples collected in 1990).

4. Results

4.1 Acidification trends: past and future

Acidification is commonly defined as a reduction in the acid neutralizing capacity (ANC). An important part of soil ANC is the pool of exchangeable base cations (Ca, Mg, Na, K), usually expressed as soil base saturation. For surface waters ANC (= alkalinity) can be defined as the difference in sum of concentrations of base cations (Ca, Mg, Na, K) minus the sum of concentrations of strong acid anions (Cl, SO_4, NO_3).

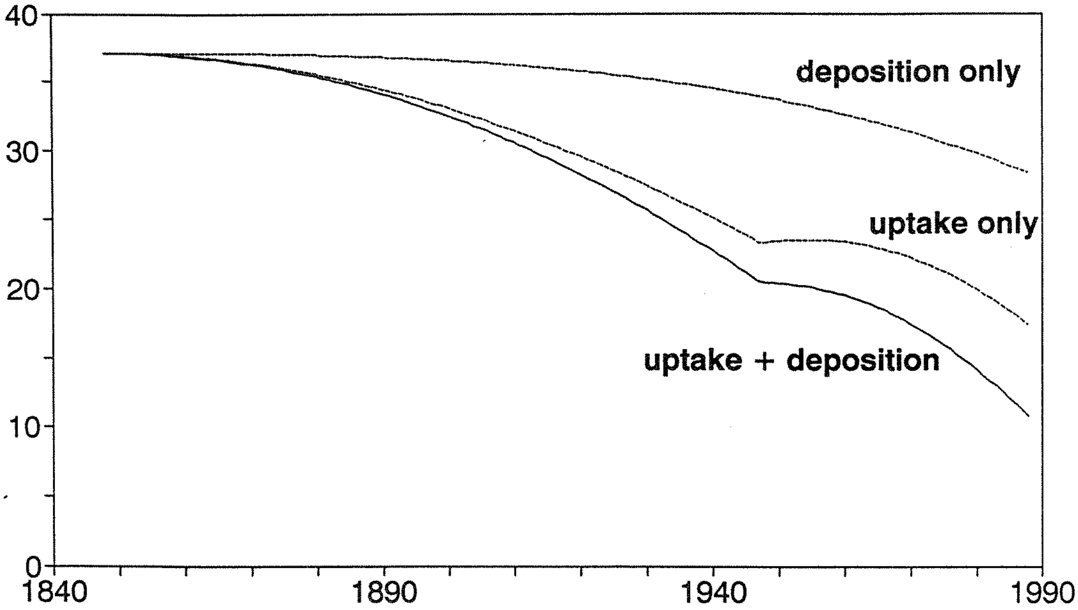
The MAGIC calibration to the data for the upper 60 cm soil at Nordmoen indicates that the soil acidified significantly over the past 140 years (Figure 5). Base saturation has declined from about 36% in 1848 to 11% in 1988 (Table 4). The decrease in base saturation from 1975 to 1988 calculated by MAGIC is comparable to the measured decrease from 18% to 11% in the O-horizon of a nearby spruce stand of about the same age (Stuanes et al. 1988). Both increased leaching due to acid deposition and uptake of base cations by the forest have contributed to this acidification. MAGIC indicates that acid deposition accounts for about 1/3 and net uptake by the forest about 2/3 of the total 4000 meq/m^2 bases lost over this 140-year period (Table 5) (Figure 6).

The prognosis for the future 50 years is continued acidification of the soil at Nordmoen again due to both uptake of cations by the growing forest and continued acid deposition. The MAGIC model fitted to the measured 1988 data can be used to evaluate future acidification under various scenarios for future uptake and sulfate deposition. Here we have made the assumption that nitrogen (both NO_3 and NH_4) uptake and deposition remain unchanged from the 1988 situation.

Table 4. Results of MAGIC application to Nordmoen. The calibration routine produces best-fit weathering rates and original base saturation for the 4 base cations.

Parameter	Units	Value
Ca saturation 1848	%	17.8
Mg saturation 1848	%	6.0
Na saturation 1848	%	1.4
K saturation 1848	%	10.8
total base saturation 1848	%	36.0
Ca weathering	$meq/m^2/yr$	0.8
Mg weathering	$meq/m^2/yr$	11.7
Na weathering	$meq/m^2/yr$	11.6
K weathering	$meq/m^2/yr$	4.0
total weathering	$meq/m^2/yr$	28.1
Ca deposition	$meq/m^2/yr$	11.0
Mg deposition	$meq/m^2/yr$	4.0
Na deposition	$meq/m^2/yr$	22.0
K deposition	$meq/m^2/yr$	4.0
total BC deposition	$meq/m^2/yr$	41.0
Ca uptake 1988	$meq/m^2/yr$	30.0
Mg uptake 1988	$meq/m^2/yr$	11.0
Na uptake 1988	$meq/m^2/yr$	0.0
K uptake 1988	$meq/m^2/yr$	27.0
total uptake 1988	$meq/m^2/yr$	68.0
SO_4 deposition 1988	$meq/m^2/yr$	63.0
BC weathering + BC deposition	$meq/m^2/yr$	69.1
BC uptake + SO_4 deposition 1988	$meq/m^2/yr$	131.0

%BS



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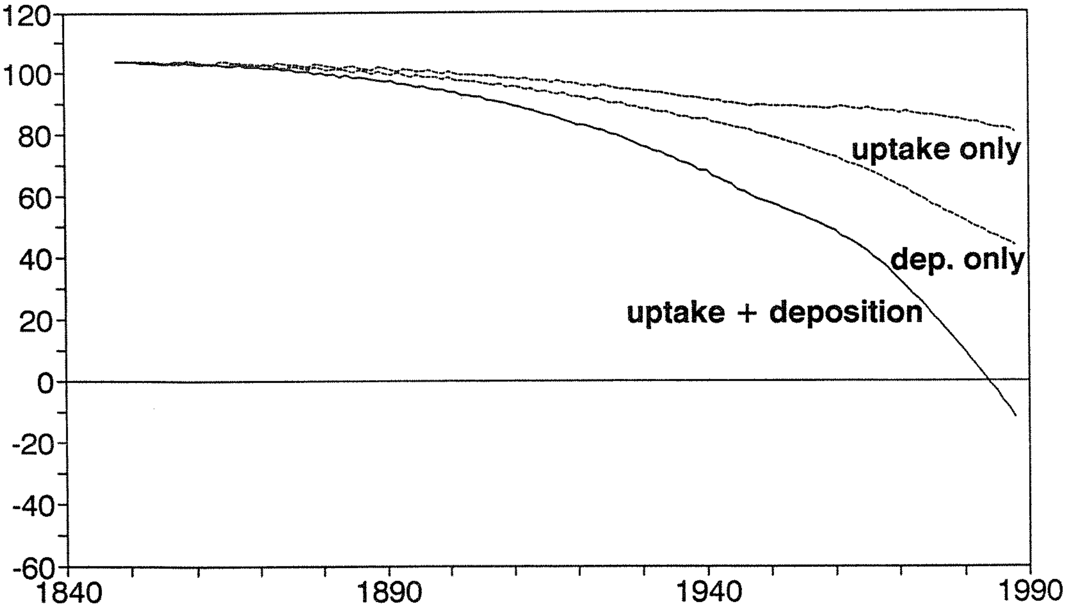

Figure 5. Historical trend in soil base saturation and soil solution alkalinity (0-60 cm) at Nordmoen as reconstructed by MAGIC (thick solid line). Also shown are the theoretical trends under the conditions that there had been no net uptake (dashed line) and no acid deposition (dotted line).

Table 5. Pool of exchangeable base cations in the upper 60 cm soil at Nordmoen as estimated by MAGIC under several scenarios. Three scenarios for the past 140 years (1848-1988) are uptake only, acid deposition only, and both (=reality). For the future starting at the 1988 measured values 4 scenarios are evaluated: 40% reduction in sulfate deposition over the period 1989-2005 and 25% reduction in uptake over the period 1989-2038 (40/25 scenario), 40% reduction in sulfate deposition and 100% reduction in uptake (40/100), 90% reduction in sulfate deposition and 25% reduction in uptake (90/25), and 90% reduction in sulfate deposition and 100% reduction in uptake (90/100). Units: meq/m^2.

	1848	1988			2038			
		uptake only	dep. only	both= meas.	40/25	40/100	90/25	90/100
Ca	2877	1440	2287	976	0	861	0	957
Mg	974	564	529	236	96	272	123	343
Na	242	213	159	137	124	140	142	164
K	1748	554	1574	452	0	613	0	633
Ca+Mg +K	5599	2558	4390	1664	96	1746	123	1933
SBC	5841	2771	4549	1801	220	1886	265	2097

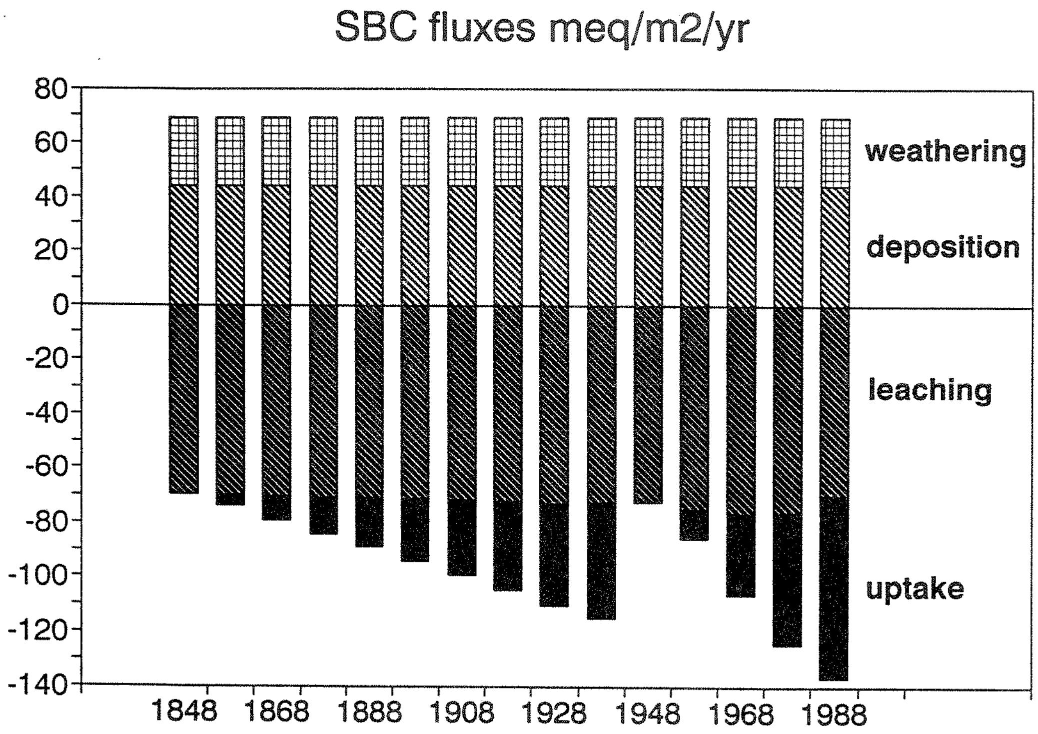

Figure 6. Historical fluxes of base cations (Ca, Mg, Na, K) at Nordmoen (0-60 cm soil) as reconstructed by MAGIC. Inputs (deposition and weathering) to the ecosystem are positive and outputs (leaching and uptake) negative. Uptake falls abruptly to zero in 1948 as a result of clearcutting.

We have chosen four scenarios for the future. These are (Figures 2 and 3):

1) 40% reduction in sulfate deposition over the period 1989-2005 then constant at this new level to 2038 and linear 25% reduction in uptake over the period 1989-2038 (40/25 scenario)

2) 40% reduction in sulfate deposition (as scenario 1) and abrupt 100% reduction in uptake 1989-2038 (40/100 scenario)

3) 90% reduction in sulfate deposition over the period 1989-2005 then constant at this new level to 2038 and linear 25% reduction in uptake over the period 1989-2038 (90/25 scenario)

4) 90% reduction in sulfate deposition (as scenario 3) and abrupt 100% reduction in uptake 1989-2038 (90/100 scenario)

For sulfate deposition the 40% reduction reflects the likely outcome of agreed and planned reductions in sulfur emissions in Europe. The 90% reduction is included here to illustrate the maximum effect of reducing emissions. For uptake the gradual 25% reduction over the next 50 years represents the most likely situation in which the existing forest (now 40-years-old) continues to grow undisturbed. The 100% abrupt reduction in uptake represents a clearcut in 1989 followed by conversion to grass and is included here to illustrate the maximum effect of reducing uptake.

MAGIC forecasts based on these 4 scenarios suggest that also in the future the rate of uptake highly affects soil acidification. Under the gradual 25% reduction (forest continues to grow) base saturation continues to decline over the next 50 years (Figure 7). With the 100% abrupt reduction in uptake (clearcutting in 1989) the decline in base saturation stops immediately and the soil begins to recover. Recovery is more rapid if sulfate deposition is reduced by 90% at the same time.

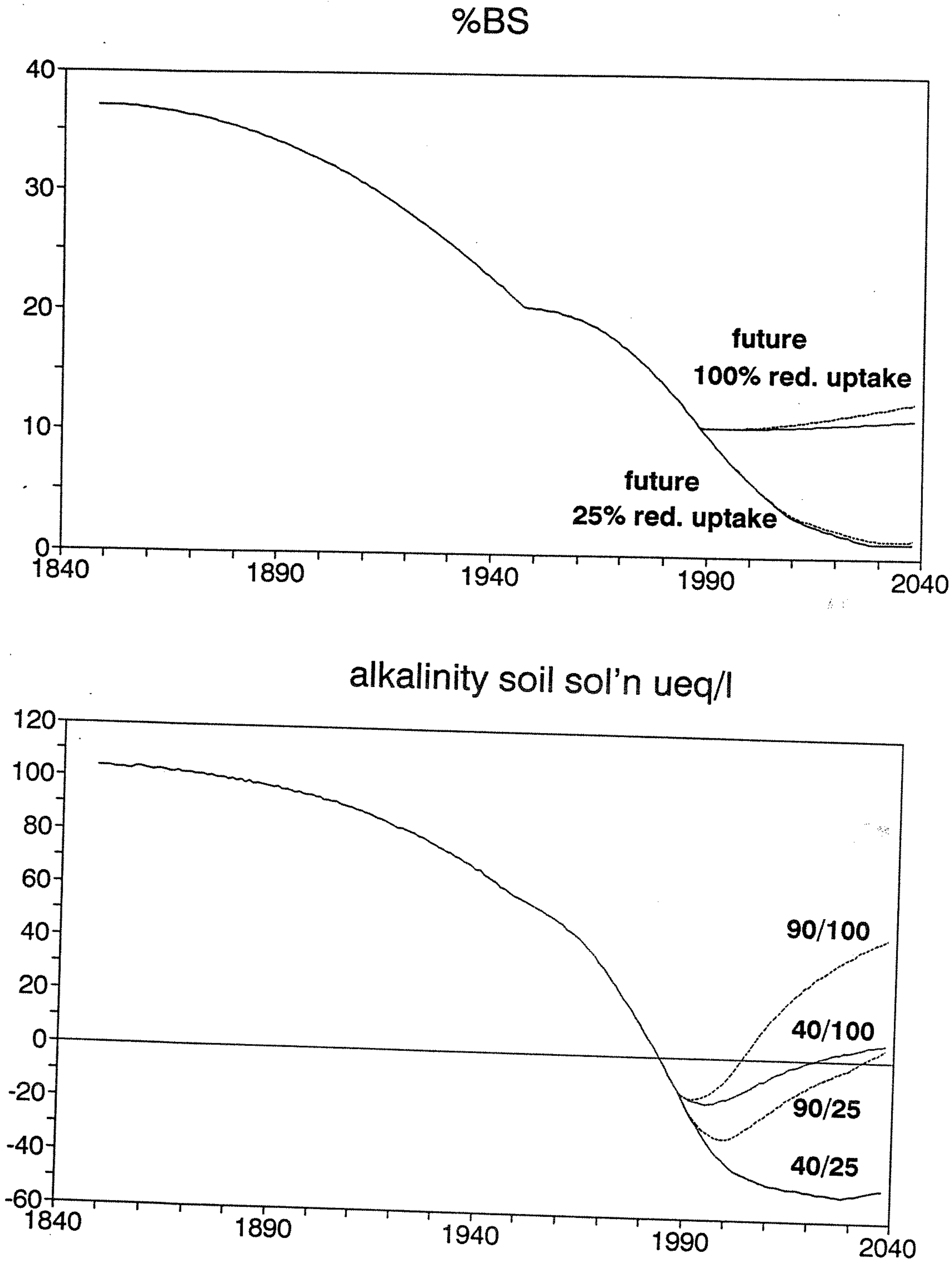

Figure 7. Future trends in soil base saturation and soil solution alkalinity (0-60 cm) at Nordmoen as predicted by MAGIC under the 4 scenarios of future acid deposition and uptake. The first value refers to % reduction in deposition, and the second to % reduction in uptake relative to conditions in 1988.

Soil solution alkalinity will show improvement in the future under all scenarios except the 40/25 scenario (Figure 7). Since this is the most realistic scenario, the prognosis for Nordmoen soil is continued decline in alkalinity as well.

4.2 Critical loads

The definition of critical load implies that each ecosystem has its intrinsic critical load. This intrinsic critical load refers to the pristine state of the ecosystem, that is before the onset of acid deposition and before the onset of land-use. For ecosystems that have been disturbed, the amount of acid deposition that can be tolerated in the future will differ from the intrinsic critical load and depend on future land-use, among other factors. For such situations the term "target load" or "tolerable load" might be more appropriate.

At Nordmoen two factors have caused historical changes in the soils that have influenced the present-day acidification status. Acid deposition has resulted in soil acidification -- a depletion in base saturation -- but also forest practices have been responsible for removal of base cations and soil acidification. These factors are additive. Because of the soil acidification in the past, Nordmoen today tolerates less acid deposition than it did several hundred years ago.

MAGIC reconstructions of the situation in 1848 allow calculation of the inherent critical load at Nordmoen. We use the Ca/Al mol/mol ratio in soil solution as the criterion, and make calculations for Ca/Al = 1 and Ca/Al = 0.5, under the requirement that the system be protected for at least 50 years. Given these conditions MAGIC indicates an inherent critical load for sulfur of 293-432 meq/m^2/yr for soil (Table 6). The lower value refers to the more stringent level for the criterion Ca/Al = 0.5.

The actual situation in 1988 at Nordmoen is, of course, different because of the historical acidification due to the combined effects of acid deposition and forest practices. Load estimates calculated on the basis of measured present-day data are substantially lower than the "inherent" critical loads. The "tolerable" load under the

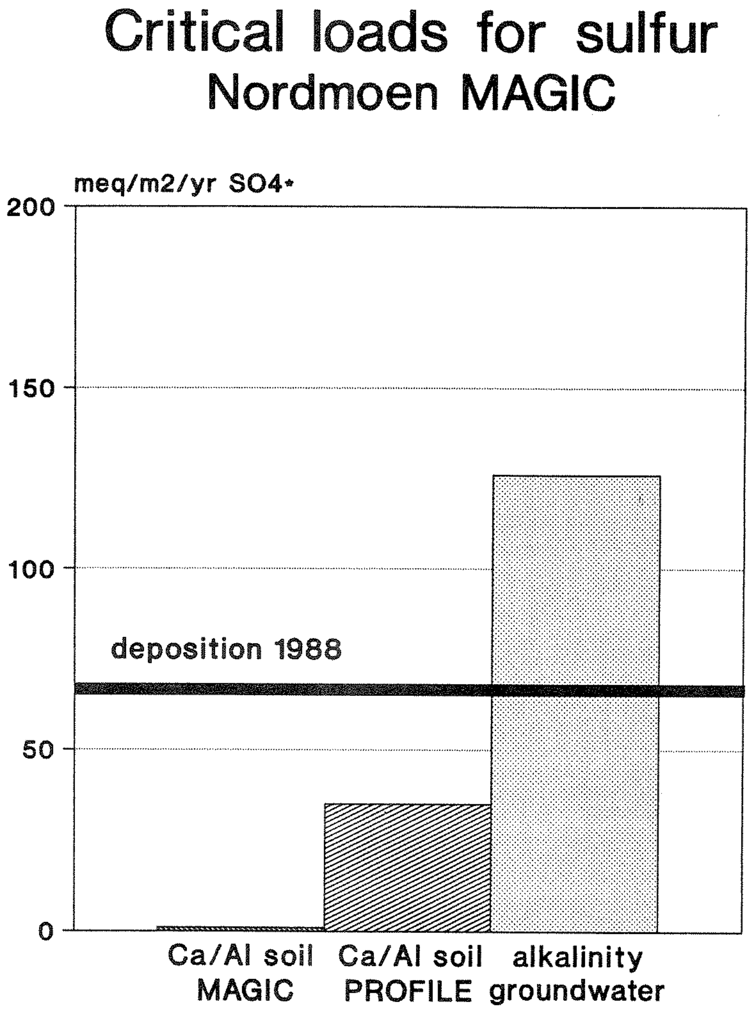

Figure 8. Critical load for sulfur at Nordmoen as estimated by several methods. Shown are MAGIC estimate for 60 cm soil under the condition that the Ca/Al ratio in soil solution be above 1 mol/mol for at least 50 years into the future, PROFILE estimate for 60 cm soil, and empirical method estimate for groundwater under the condition that alkalinity exceed 0 μeq/l. Also shown is present-day deposition (wet+dry) at Nordmoen. Units: meq $SO_4/m^2/yr$.

conditions that the soil solution Ca/Al molar ratio be above 1 or 0.5 is now 0 meq $SO_4/m^2/yr$ (Table 6). This estimate assumes that forestry practices will continue for the next 50 years at the same intensity as the past 50 years. If, however, the future uptake by the growing forest stops the "tolerable" load is 47 or 105 meq $SO_4/m^2/yr$, respectively for the 2 Ca/Al values.

Table 6. Summary of critical load estimates for Nordmoen by means of several methods recommended by the manual (Sverdrup et al. 1990). Units: meq $SO_4/m^2/yr$.

	Method	Conditions	Criterion			
			Ca/Al		alkalinity	
			> 1	> 0.5	> 50	> 0
1.	"Intrinsic" critical load. MAGIC. Situation in 1848.	60 cm soil. Protect 50 years.	293	432	61	106
2.	"Tolerable" load. MAGIC. Situation in 1988.	60 cm soil. Protect 50 years. Continued uptake.	0	0	0	15
3.	"Tolerable" load. MAGIC. Situation in 1988.	60 cm soil. Protect 50 years. No uptake.	47	105	8	45
4.	Critical load. PROFILE Situation in 1988.	60 cm soil. Static.	35			
5.	Critical load. Mass-balance steady-state method. Situation in 1848.	60 cm soil. Static.				44
6.	Critical load. Mass-balance steady-state method. Situation in 1988.	60 cm soil. Static.				-24
7.	Critical load. Empirical method. Situation in 1988.	Groundwater. Static.				126

Of the other methods suggested by the critical loads handbook (Sverdrup et al. 1990), the PROFILE model gives a critical load of 35 meq $SO_4/m^2/yr$. All of these estimates apply to the 0-60 cm soil at Nordmoen, and reflect critical loads to protect the forest using the Ca/Al criterion.

These estimates can be compared to estimated critical loads for the surface waters at Nordmoen. Here we use data for groundwater inasmuch as there are no surface waters in the immediate vicinity of the Nordmoen site. The groundwater is affected by processes in several meters of soil and overburden and thus has substantially higher concentrations of base cations and alkalinity than the soil leachate at 60 cm (Table 1). The empirical method for waters gives a critical load estimate of 126 meq $SO_4/m^2/yr$ (Table 6).

5. Discussion

Application of the MAGIC model to the data from Nordmoen indicates that uptake of base cations by the growing forest and acid deposition have caused extensive acidification of the soil in the rooting zone. The soil solution data for 1986-88 show low concentrations of the base cations and high concentrations of aluminum. If the Ca/Al ratio is a true indicator of damage to roots, then the 40-year-old forest at Nordmoen is on the brink of damage.

The nutrient cycling data indicate that net uptake by the forest is large relative to inputs from weathering. The flux data suggest that soil acidification is continuing. The forest is thus threatened by nutrient imbalance. This conclusion is supported by the model results.

The estimated "tolerable" load for Nordmoen soil today is 0. Unless uptake is greatly diminished in the near future, the soils will continue to acidify to the point at which the pool of base cations is severely depleted. The "intrinsic" critical load of the soil at Nordmoen is 300-400 meq $SO_4/m^2/yr$, but the combined effects of forestry and acid deposition over the past 140 years has greatly diminished the ability of the soil to tolerate acid deposition.

Critical load estimated by several of the methods recommended by the manual (Sverdrup et al. 1990) differ widely depending upon method, condition, and criterion used (Figure 8). Based on the present situation in 1988, the "tolerable" load for the 60 cm soil is much less than that for groundwater (Table 6). Nordmoen is thus a site in Norway at which the soil and forest is more sensitive than surface waters. This contrasts sharply with the situation over large areas of Norway, and is readily explained by the deep soils at Nordmoen which will deliver more base cations and alkalinity to surface waters than do the thin and patchy soils typical of most of the country.

Mapping of critical loads in Norway should focus on the most sensitive part of the ecosystem. For areas with thin and patchy soils, surface waters appear to be more sensitive by a factor of 2 relative to soils and forests (Wright et al. 1990). For Nordmoen the reverse is the case. Soil depth alone or in combination with some other criterion such as base saturation may provide the means by which the relative sensitivity of soils and surface waters can be mapped in Norway. For regions with thick soils such as Romerike, parts of Hedmark and Oppland, and Finnmarksvidda, mapping of critical loads might best be concentrated on forests and soils.

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