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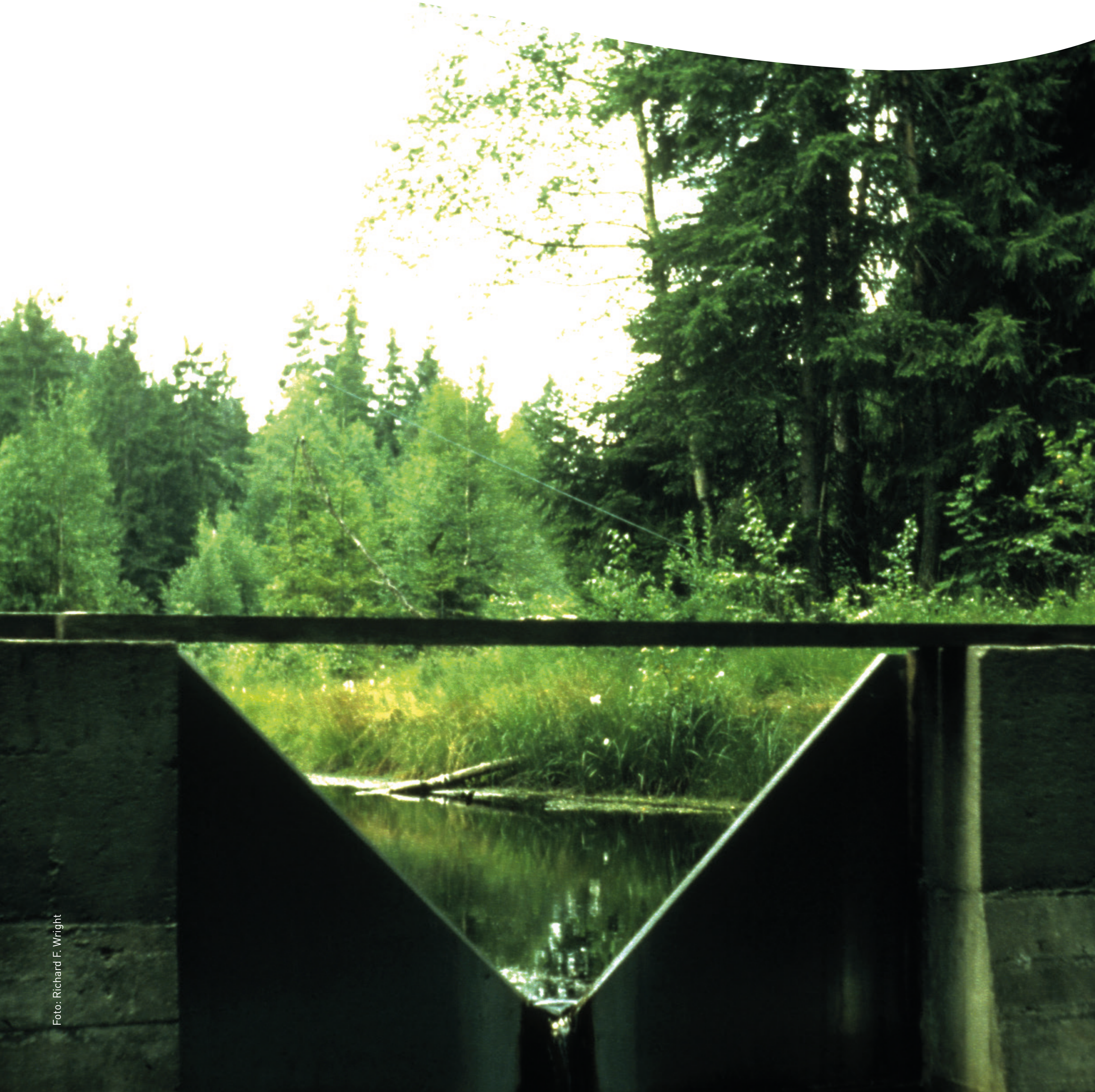
Intensified forestry as a climate mitigation measure – how can it affect critical loads for S and N deposition?



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Norwegian Institute for Water Research

REPORT

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Summary

More intensive forestry has been proposed in Norway as a climate mitigation measure. Growing forests capture CO_2 from the atmosphere and the harvested biomass can comprise a carbon sink. Changes in forestry practices, however, might adversely affect the sensitivity of surface waters to acidification in poorly buffered ecosystems. Increased removal of biomass can accelerate the depletion of base cations from the soil. We calculated the effect of increased harvest intensity on the critical load of acidity to surface waters at two forested sites in Norway, Birkenes in Vest-Agder, and Langtjern in Buskerud. Model simulations of water quality, given several scenarios of future forest harvest, were carried out by applying the dynamic biogeochemical model MAGIC. Calculations of critical loads were based on the SSWC and FAB steady-state models. The results indicate that change from stem-only to whole-tree harvest will decrease the critical load of acidity, i.e. the ecosystem can tolerate less sulphur deposition. The critical load of nitrogen, on the other hand, will increase because more nitrogen is removed from the catchment. With whole-tree harvest, the catchments can tolerate more N deposition than with traditional stem-only harvest before significant leaching of NO_3 and re-acidification occurs. Increased harvest intensity thus entails a trade-off: surface waters in sensitive areas will tolerate less sulphur deposition but more nitrogen deposition.

Four keywords	Fire emneord
1. Water quality	1. Vannkvalitet
2. Forestry	2. Skogbruk
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Intensified forestry as a climate mitigation measure -

How can it affect critical loads for S and N deposition?

Preface

During the work in the SURFER project (NFR project number 267481), a Norwegian research project on the effects of intensified forest management on water quality, the question arose as to what extent various forest harvest practices can affect the critical loads of acidity for surface waters. The work was supported by the Norwegian Environment Agency and the Research Council of Norway (SURFER, project no. 267481). The data are largely from the Norwegian national programme for monitoring the effects of long-range transported air pollutants. We thank Wenche Aas (Norwegian Institute for Air Research) for deposition data, Nicholas Clarke (Norwegian Institute of Bioeconomy Research) for forest data, B. Jack Cosby (Centre for Ecology and Hydrology, UK) and Filip Oulehle (Czech Geological Survey, CZ) for help with the MAGIC modelling, Maximillian Posch (International Institute for Applied Systems Analysis, AU) for advice on critical load calculations, and Heleen de Wit (NIVA) and Kari Austnes (NIVA) for comments on the report. Contact person at the Norwegian Environment Agency has been Gunnar Skotte.

Grimstad, December 2019

Øyvind Kaste

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Summary

More intensive forestry practices have been proposed in Norway as a climate mitigation measure. Increased growth and removal of biomass from forests can contribute to more binding of atmospheric CO_2. Change in forestry practices might adversely affect the sensitivity of surface waters to acidification, especially in acid-sensitive areas such as southeastern and southernmost Norway. Here, we calculated the effect of changing forestry practices on the critical load of acidity to surface waters at two forested sites in Norway, Birkenes in Vest-Agder, and Langtjern, Buskerud. These sites are part of the Norwegian monitoring programme for long-range transported air pollutants and their soils have low buffering capacity. The sites are typical of forested catchments in acid-sensitive terrain receiving harmful levels of acid deposition. Birkenes has productive forest while the forest at Langtjern is in the lowest productivity class.

The calculations were based on the steady-state critical load models SSWC (Steady-State Water Chemistry) and FAB (First-order Acidity Balance) and the dynamic model MAGIC (Model for Acidification of Groundwater In Catchments). Three forest harvest scenarios were examined: no harvest, stem-only harvest (SOH) and whole-tree harvest (WTH). In WTH needles and branches were assumed removed in addition to the stem.

The results indicate that the critical load of acidity, a measure for the sensitivity of ecosystems to buffer acid deposition, will decrease with increased removal of biomass from the ecosystem. Conventional stem-only harvest removes only the stems from the ecosystem. Whole-tree harvest, however, entails removal of also the needles and branches, biomass that contains large amounts of base cations and nitrogen. The regrowing forest must then take up these elements from the soil. The effect is largest at Birkenes, because here the forest is more productive. The ecosystem will tolerate lower levels of sulphur deposition before a critically poor water quality occurs, because of higher removal of base cations. However, the ecosystem will tolerate higher levels of nitrogen deposition before water quality reaches a critical level related to significant nitrate leaching because of increased removal of nitrogen in biomass. Increased forest harvesting thus entails a trade-off – the ecosystem will tolerate lower levels of sulphur deposition, but higher levels of nitrogen deposition. Sulphur deposition remains the most important factor for surface water acidification. Thus, at current levels of sulphur deposition, intensified forestry is a factor that promotes surface water acidification or delays chemical recovery.

These scenarios all assume that 100% of the catchment forest was affected, either by stem-only or whole-tree harvest. In practice, conventional harvesting techniques do not remove 100% of the standing biomass. Buffer strips are left along open water and wetlands and some parts of the catchment may not be accessible or may not have mature trees.

Nevertheless, transition to removal of a larger portion of standing biomass with WTH as compared to SOH will result in a long-term depletion of in soil base cations and a setback in the positive trend in stream acidification status (as expressed in Acid Neutralizing Capacity, ANC) unless further reductions in acid deposition are achieved. In sites with productive forest and high exceedance of critical loads (such as Birkenes), additional removal of base cations by WTH will lead to a longer recovery time. There will be a need for further reductions in S deposition to achieve recovery from acidification. For sites with low productivity and no or little exceedance of critical loads (such as Langtjern), forest harvest practices will have less impact on the acidification status of surface waters. Forest and environmental managers should carefully consider surface water sensitivity to acidification when selecting sites for fertilisation and other intensive forestry practices.

Sammendrag

Tittel: Intensivert skogbruk som klimatiltak – hvordan kan det påvirke tålegrenser for S og N deposisjon?
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Et mer intensivert skogbruk er i Norge blitt foreslått som et klimatiltak. Økt skogvekst og fjerning av biomasse i form av hogst kan bidra til økt opptak og lagring CO_2 fra atmosfæren. Overgang til et mer intensivert skogbruk kan imidlertid gi forsuringseffekter, spesielt i områder med forsuringsfølsom berggrunn slik som i den sørlige delen av Norge. Vi har estimert effekten av ulike skogbruksformer på tålegrenser for forsuring i to norske skogfelter; Birkenesfeltet i Vest-Agder og Langtjern i Buskerud fylke. Begge feltene har vært en del av det nasjonale overvåkingsprogrammet for effekter av langtransporterte luftforurensninger siden starten i 1980. Feltene er typiske representanter for skogområder med forsuringsfølsom berggrunn og som fortsatt er utsatt for sur nedbør. Birkenesfeltet er nær 100% dekket av produktiv skog, mens nedbørfeltet rundt Langtjern er dominert av lavproduktiv skog.

Beregningene er basert på tålegrense-modellene SSWC (Steady-State Water Chemistry model) og FAB (First-order Acidity Balance model), samt den dynamiske forsuringsmodellen MAGIC (Model for Acidification of Groundwater In Catchments). Tre skogbruks-scenarier ble inkludert i modellene: (1) ingen hogst, (2) tradisjonell hogst med kun uttak av trestammer, og (3) heltre-hogst som inkluderer grener, nåler og topper.

Resultatene indikerer at tålegrensen for forsuring vil avta med økende intensitet i skogbruket, dvs. gradvis større uttak av biomasse i form av trevirke. Effekten var størst i Birkenesfeltet hvor skogen er mer produktiv enn i det høyereliggende Langtjern-området. Økosystemene vil tåle mindre svoveldeposisjon etter hogst på grunn av at uttaket av skogbiomasse fjerner basekationer. Effekten vil være aller størst med heltre-hogst, hvor også grener og topper tas ut av skogen. Med heltre-hogst vil imidlertid økosystemene kunne tåle mer nitrogendeposisjon fordi uttaket av skogbiomasse har fjernet nitrogen som er lagret i stammer, samt grener, nåler og topper som er spesielt rike på nitrogen. Et mer intensivert skogbruk innebærer derfor en avveining (trade-off) ved at systemet kan tolerere mindre svoveldeposisjon, men høyere nitrogendeposisjon. Svoveldeposisjonen er derfor fortsatt en nøkkelfaktor i forbindelse med vannforsuring, og med dagens deposisjonsnivå vil større biomasseuttak i forbindelse med et mer intensivert skogbruk kunne føre til re-forsuring av vann i forsuringsfølsomme områder.

Det må bemerkes at modellsimuleringene er basert på at all skog i feltene hugges, enten ved tradisjonell hogst eller ved heltre-hogst. I virkeligheten vil ofte ikke et helt nedbørfelt bli omfattet av hogst, og det er dessuten pålegg om at det skal spares en buffersone mot bekker som har permanent vannføring hele året.

En overgang til fra tradisjonell hogst til større biomasseuttak i form av heltre-hogst vil over tid føre til et tap av basekationer som i forsuringsfølsomme områder vil gi lavere syrenøytraliserende kapasitet (ANC) og økt vannforsuring, med mindre det oppnås større reduksjoner i deposisjonen av sure komponenter fra langtransportert forurenset luft og nedbør. I områder med produktiv skog og store overskridelser av tålegrensene for forsuring (slik som i Birkenes) vil et ekstra uttak av basekationer

ved heltre-hogst føre til en langsommere forbedring av forsuringstilstanden etter at deposisjonen av sure komponenter er redusert gjennom internasjonale avtaler om utslippsreduksjoner. Det vil med andre ord medføre at svoveldeposisjonen må reduseres ytterligere for å kompensere for tapet av basekationer. I områder med lavproduktiv skog og små eller ingen overskridelser av tålegrensenene for forsuring (slik som ved Langtjern) vil valg av hogstmetode ha mindre betydning for forsurings-tilstanden. Det er derfor viktig at skog- og miljøforvaltningen tar hensyn til stedsspesifikke forhold og vannforekomstenes følsomhet for forsuring ved planlegging av gjødslingstiltak og ved valg av hogstmetoder.

1 Introduction

Critical loads of acid deposition (sulphur S and nitrogen N) for surface waters in Norway are generally based on the assumption of steady state. This implies that present-day forestry practices will not change in the future. It is assumed that the use of the forest through cutting and planting will continue at the same rate as it has done in the past. Recently, however, Norway has opened for changes in forestry practices to promote forest growth. This policy aims to increase the binding of CO_2 from the atmosphere – as a climate mitigation measure (Haugland et al. 2014, Flugsrud et al. 2016). Measures include removal of larger amounts of biomass in harvesting, and increased use of fertilisation with nitrogen (N) to stimulate growth of mature forests approximately one decade prior to harvesting. In addition, there has been increased focus on the use of wood as a substitute for fossil fuels – part of the 'green shift'. Increased growth of forests and increased removal of timber may lead to impoverishment of nutrients in the soil. Decreased pools of base cations such as calcium (Ca), magnesium (Mg) and potassium (K) imply greater sensitivity to acid deposition – i.e. lower critical load of acidity. On the other hand, removal of nitrogen in biomass may allow for more N to be deposited from the atmosphere before leaching of N reaches harmful levels for surface waters – i.e. higher critical load of N. Possible effects of soil disturbance, changes in hydrology and associated leaching of elements related to forestry harvesting is outside the scope of this report, only effects from changes in ecosystem pools of base cations and nitrogen for critical loads are considered.

The effects of fertilisation and changed forestry practices on water quality in Norwegian surface waters is the subject of SURFER (Surface waters: The overlooked factor in the forestry climate mitigation debate?), a research project 2017-19 led by NIVA (the Norwegian Institute for Water Research) and financed by the Research Council of Norway. SURFER includes a large-scale forest fertilisation operation (at the Lake Glitrevann, near Drammen, Buskerud) and model simulations of water quality given several scenarios of future forestry practices (using the acidification model MAGIC applied to the forested catchment at Birkenes, Aust-Agder).

Two steady-state models – one empirical and one process-oriented – are commonly used to calculate critical loads of acidifying deposition (S and N) for surface waters (Henriksen and Posch 2001). The empirical Steady-State Water Chemistry (SSWC) model allows the calculation of critical loads of acidity and their exceedances for any S deposition scenario, given the present N leaching level (UBA 1996, 2004). The SSWC model does not consider any other N leaching scenarios since no equations for N sources and sinks are included. The process-oriented First-order Acidity Balance (FAB) model includes considerations of long-term N storage and leaching. FAB calculates separate critical loads of S and N and their exceedances for any scenario of S and N deposition (Posch et al. 1997, Henriksen and Posch 2001). Both models use the same approach for calculating the pre-acidification leaching of non-marine base cations and also the same ANC_{limit}, the lowest ANC flux that does not damage selected biota. In the negotiations for the multi-pollutant, multi-effect protocol signed in Gothenburg in December 1999 (UNECE 2014), the FAB model was used as a basis for calculating critical loads for surface waters. The critical load of sulphur and nitrogen for surface waters is the amount of S and N that can be deposited on a catchment without giving rise to adverse effects on key aquatic organisms.

Given our understanding of the importance of ecosystem pools of nitrogen and base cations for sensitivity to surface water acidification based on decades of research on biogeochemical cycles (Wright et al. 2010) , it is clear that a change in forestry practices in the catchment will affect the critical load of sulphur and nitrogen. Such changes over time mean that the assumption of steady-state no longer holds, and a time-dynamic model is called for. One such model is MAGIC (Model for Acidification of Groundwater In Catchments) (Cosby et al. 1985, Cosby et al. 2001) a dynamic process-oriented model for soil and water acidification that has been widely applied is Europe and North America.

Here we evaluate the effect of changing forestry practices on critical loads at two forested sites in southern Norway, Birkenes in Vest-Agder and Langtjern in Buskerud. Birkenes has productive spruce forest, while Langtjern has low-productive mixed spruce-pine-birch forest. The sites have extensive long-term data and are part of the Norwegian monitoring programme for long-range transported air pollutants. For Birkenes we take the results from the MAGIC simulations of various harvest operations and fertilisation by nitrogen at Birkenes previously done in the SURFER project (Valinia et al. In prep.). These are scaled to Langtjern using an earlier calibration of MAGIC to Langtjern (Larssen 2005). We calculate critical loads for acidity and nitrogen given three scenarios of forest harvest – no harvest (i.e. no removal of biomass), conventional stem-only harvest (SOH), and whole-tree harvest (WTH), the latter in which the tops and branches are also removed, and whether or not the stand was fertilised 10 years prior to cutting. In all cases the new stands were assumed to be thinned after 30 years. The scenarios all assume future S and N deposition to follow that of the revised Gothenburg protocol of the Convention on Long-Range Transported Air Pollutants (CLTRAP) (UNECE 2014) and to decline slightly to the year 2030 and then remain constant to the year 2100.

2 Methods and input data

2.1 Study sites

The Birkenes catchment is located in Vest-Agder County about 20 km north of Kristiansand on the south coast (Figure 1). The catchment area is 0.41 km^2, and the elevation is 200-300 m.a.s.l. The vegetation is mainly 100-year old Norway spruce (*Picea abies*) with some Scots pine (*Pinus sylvestris*) and birch (*Betula pubescens*) and an undergrowth of mosses, blueberry, and fern. Soils of brown earth and podzols have developed in a shallow layer of glacial till on granitic bedrock with peat deposits on poorly drained sites. On the slopes, well-drained thin organic layers on gravel or bedrock are common. The catchment is drained by three small second-order streams, which converge about 150 m above the V-notch weir. The site for precipitation and air sampling is located about 500 m north of the catchment. The site receives significant sea-salt deposition, which has considerable influence on the streamwater chemistry. More details are given by Larssen (2005).

Langtjern is a lake and catchment located 120 km northwest of Oslo in the county of Buskerud in southeastern Norway (Figure 1). The area is underlain by felsic gneisses and granites; thin soils are developed on till of generally the same lithology as the bedrock. Within the Langtjern catchment, 63% of the area is covered by mixed spruce (*Picea abies*), pine (*Pinus sylvestris*), and birch (*Betula pubescens*) forest, 16% by peat deposits or bogs, and 16% is exposed bedrock. The catchment area of Lake Langtjern is 4.69 km^2. The lake has a surface area of 0.227 km^2. More details are given by de Wit et al. (2014). The station for precipitation and air chemistry is located about 6 km east of the catchment; it was moved in 1995 from Gulsvik to nearby Brekkebygda.

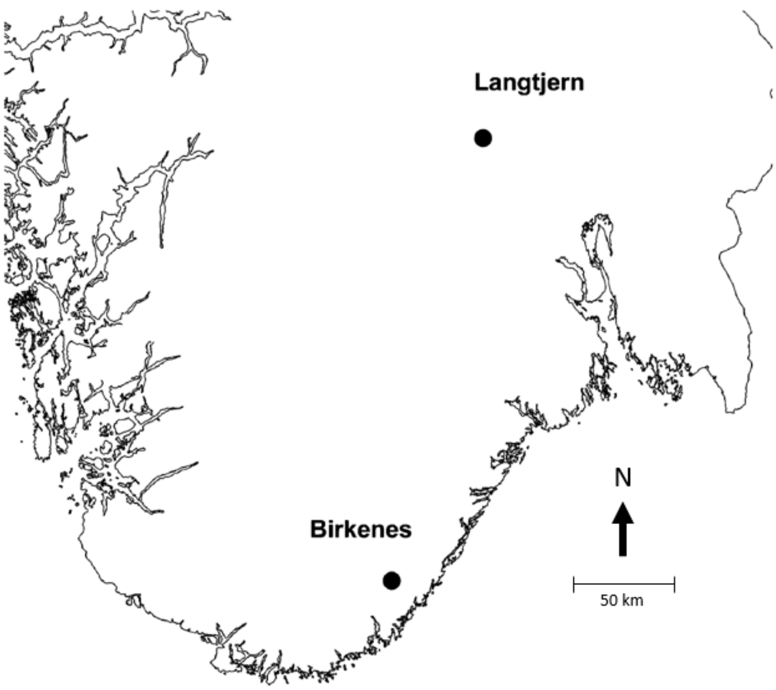

Figure 1. Map of southern Norway showing location of the two sites Birkenes and Langtjern

Table 1. Characteristic Data for the Birkenes and Langtjern calibrated catchments

	Units	**Birkenes**	**Langtjern**
catchment area	km^2	0.41	4.69
latitude	degrees north	58.38	60.37
longitude	degrees east	8.25	9.73
altitude	meters above sea level	190	516
Land cover			
Forest	%	90	74
Impediment and open water	%	3	5
wetlands	%	7	21
Bedrock		Granite, biotite	Gneiss, granite

2.2 Short description of the critical loads concept

The atmospheric transport of acidifying compounds from industrial emissions and the subsequent deposition of such compounds, resulting in acidification of surface waters and negative effects on aquatic biota, led to the development of the concept of critical loads for acidification of surface waters. These critical loads quantify the acid deposition that an area can tolerate without negative effects on aquatic biota (in Norway often represented by brown trout). By comparing the critical loads with deposition data one can identify areas where critical loads are exceeded, and thus at risk of surface water acidification (Austnes et al. 2018). The concept of critical loads has been a scientific tool for assessing the problem of acidification and for the international work on reducing acidifying emissions in Europe and North America. It is a basis of both the sulphur protocol (1994) and the multi-pollutant protocol (1999) (the Gothenburg protocol) of the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) (www.unece.org/env/lrtap /status/lrtap_s.html).

The concept of critical loads has been widely accepted in Europe as a basis for designing control strategies to reduce regional and transboundary air pollution. The concept was developed and adopted for use under the CLRTAP. To gain insight into the magnitude and spatial variation of critical loads, the Executive Body of CLRTAP set up an International Mapping Programme on Critical Levels/Loads under the Working Group on Effects. Critical loads are calculated for several types of ecosystems including forests and surface waters. Critical loads data from individual countries are collated, mapped and reported by the Mapping Programme's Coordination Centre for Effects, see e.g., Posch et al. (1999).

Critical loads can be estimated using steady-state models. The most commonly used models for surface waters are the Steady-State Water Chemistry (SSWC) model and the First-order Acidity Balance (FAB) model (Henriksen and Posch 2001). Fundamental to both models is the critical limit of acid neutralising capacity (ANC), i.e. the ANC_{limit}. The critical limit is the link between surface water chemistry and biological response, and is set to avoid harmful effects on selected biota. The most recent update of the models and methods is given by CLRTAP (2017).

If the assumption of steady-state is no longer valid, calculation of critical load will require use of a (time-) dynamic model. New forestry practice at a site is one type of change that necessitates a dynamic model approach. In the cases here we combine the steady-state and dynamic model approaches. We assume that the various forest practice scenarios differ only in the type of clearcutting (no harvest, stem-only harvest SOH or whole-tree harvest WTH) and whether the stand was fertilised 10 years prior to cutting. After cutting the forest was assumed to re-grow at the same rate regardless of previous forestry practice. In all cases the stands were assumed to be thinned after 30 years. Thus, the system reverts to a new steady state for the 80 years following clearcut.

2.3 Model descriptions

2.3.1 Steady-State Water Chemistry Model (SSWC)

The (modified) Steady-State Water Chemistry (SSWC) model (Henriksen et al. 1992) estimates the weathering rate from the present-day base cation flux and uses the so-called F-factor to account for the part of present base cation leaching due to ion exchange processes in the catchment soils. The buffer required to protect selected biota is represented by the ANC_{limit}. The present value for the ANC_{limit} is based on the response of fish (brown trout) to the ANC of the lake-water (and will, in general, be a function of catchment characteristics).

The critical load of acidity CL(A) is defined as:

$$Cl\ (A) = BC^{*}_{dep} + BC_{w} - BC_{u} - ANC_{limit} - (SO_{4w}),$$

where $BC^{*}dep$ is the non-marine deposition of base cations, BC_w is the weathering rate of base cations, BC_u is the net uptake of base cations in biomass (the average annual removal of base cations due to harvesting), ANC_{limit} is the ANC above which no harmful effects on biota occur, and SO_{4w} is the weathering rate of sulphate.

2.3.2 First-order acidity balance model (FAB)

The First-order Acidity Balance (FAB) model for calculating critical loads of S and N for a waterbody takes into account sources and sinks within the waterbody and its terrestrial catchment (Henriksen and Posch 2001). The base cation and Acid Neutralizing Capacity (ANC) part of the model is taken from the SSWC model. The FAB model takes into account the various sources and sinks of N in the terrestrial and aquatic ecosystems.

The amount of N entering the waterbody from the terrestrial catchment is:
$$N_{in} = N_{dep} - N_{im} - N_{u} - N_{de},$$

where N_{dep} is the total N deposition, N_i is the long-term net immobilisation of N in the catchment, N_{de} is N lost by denitrification, and N_u the net growth uptake of N, all per unit area. The effects of nutrient cycling are ignored, and the leaching of ammonium is considered negligible, implying its complete uptake and/or nitrification in the terrestrial catchment. The FAB model assumes that all N deposition not immobilised or taken up in vegetation (and removed from the catchment) will leach out in runoff as nitrate (NO_3), and thus contribute to surface water acidification.

The FAB model is based on the observation that there is a trade-off between the amount of S deposition and the amount of N deposition a given ecosystem can tolerate. If S_{dep} is at the maximum given by CL(A), then the N_{dep} must be minimum, i.e. $Cl_{min}N$ is equal to $N_{im}+N_u$. If S_{dep} is at the minimum (set to zero), then the N_{dep} can be maximum, i.e. $CL_{max}N$ equals $CL(A)+N_{im}+N_u$.

2.3.3 The MAGIC model

MAGIC (Model for Acidification of Groundwater In Catchments (Cosby et al. 1985, Cosby et al. 2001) is a process-oriented dynamic model of soil and surface water chemistry and has been widely used to assess critical and target loads for surface waters. The MAGIC model was developed to predict long-term effects of acid deposition on soil and surface water chemistry (Cosby et al. 1985, Cosby et al. 2001). It calculates annual or monthly concentrations of ions in soil solution and surface water using mathematical solutions to simultaneous equations describing sulphate adsorption, cation exchange, dissolution–precipitation speciation of aluminium, and dissolution–speciation of inorganic and organic carbon. The model accounts for the mass balance of major ions by simulating ionic fluxes from atmospheric inputs, chemical weathering, net uptake in biomass, and loss to runoff.

2.4 Forest management scenarios

The scenarios here assume that the historical forest management (1850-2017) is selective cutting of 1% trees per year. At Birkenes the age of the forest in 1990 was 95 years. At Langtjern the forest was about 75 years in 2010. We evaluated three forest harvest scenarios with and without forest fertilisation: no cutting or removal of biomass, clearcutting with stem-only harvest (SOH) and clearcutting with whole-tree harvest (WTH). Whole-tree harvest differs from SOH in that the needles and branches are removed in addition to the stems. Forest fertilisation was assumed to be 150 kg N/ha applied 10 years prior to clearcutting. The new forest was assumed to be thinned 30 years after clearcut, with the thinning residues left on the ground. The scenarios were run from the year 2020 to 2100. For all these we assumed that future deposition of S and N would decline slightly to the year 2030 from present-day levels following implementation of the revised Gothenburg protocol to the CLRTAP and then be constant to the year 2100.

2.5 Input data for the critical load calculations

The input data for the critical load calculations come mainly from present-day measurements. MAGIC was used only to estimate the weathering rates. MAGIC offers a more rigorous method to calculate weathering rates than the F-factor method used in the original formulation of the SSWC model.

Deposition fluxes were estimated at each site from the measured flux of elements in streamwater, under the assumption that all the chloride (Cl) and sulphate (SO_4) in streamwater originates from atmospheric deposition. The measured deposition at NILU's stations Birkenes and Brekkebygda are not used directly for two reasons: dry deposition may not be sufficiently included, and the measured precipitation amount may not be representative for the entire catchment. The latter is especially true for Langtjern, where the measured precipitation volume in many years is less than the measured runoff volume at the weir on the outlet of Lake Langtjern. Further it is assumed that the Cl is accompanied by SO_4 and the base cations Ca, Mg, Na, and K in proportion to that in seawater. An additional input of non-marine Ca is assumed to follow pollutant SO_4 (SO_4^*). Deposition of nitrate (NO_3) and ammonium (NH_4) is assumed to be that relative to the fluxes to SO_4^* in precipitation measured at the NILU stations Birkenes and Brekkebygda. Valinia et al. (In prep.) give details.

The MAGIC calibrations for Birkenes and Langtjern of Larssen (2005) were used, *albeit* modified by Valinia et al. (In prep.) as part of the SURFER project. The modifications make use of data for forest parameters at Birkenes published by Røsberg and Stuanes (1992) (Table 2). These data were scaled to Langtjern based on estimates of standing biomass and stem volume growth rates for Birkenes and Langtjern (Table 3).

The uptake (i.e. removal) rates were calculated from the mass of each element in standing biomass, for SOH only that in the stems, while for WTH also that in the needles and branches, divided by the average age of the trees.

The long-term rate of N immobilisation (N_i) was estimated from the total N pool in the soil divided by 10 000, the number of years since the last glaciation, and thus the onset of soil formation and N accumulation in the soil. De-nitrification (N_{de}) was assumed to be negligible, as was N fixation.

Table 2. C, N and nutrient cations in biomass and soil at Birkenes based on data from the Norwegian monitoring programme. Data are averages for plots R1 and R2 from Røsberg and Stuanes (1992).

Component	**organic matter**	**C**	**Ca**	**Mg**	**K**	**N**	**C/N**
Units	kg/ha	mmol/m2	meq/m2	meq/m2	meq/m2	mmol/m2	mol/mol
trees							
foliage	15270	64958	406	107	180	1118	58
branch	12454	54192	217	37	100	596	91
bole	46993	246213	399	103	228	496	496
stump	4626	25558	57	8	18	71	358
roots	29453	124896	140	45	69	393	318
total	108796	515817	1219	300	595	2675	193
understory	2736	11729	57	16	43	300	39
forest floor O horizons	59134	252156	885	420	271	5168	49
soil extractable			913	210	448		
soil total	115555	478633				26679	18

Table 3. Standing stock and annual increment in the boles (stems) of the trees at Birkenes (1990) and Langtjern subcatchment LAE03 (2008). Data from Røsberg and Stuanes (1992) (Birkenes) and de Wit et al. (2014) and A. Granhus (pers. comm.) (Langtjern).

	Unit	**Birkenes 1990**	**Langtjern 2008**
Standing stock	m^3/ha	314	78
Annual increment	m^3/ha/yr	3.6	1.4

Table 4. Measured and calculated parameters for the SSWC and FAB models. Data are from the most recent year in the MAGIC calibrations: Birkenes 2018 from (Valinia et al. In prep.) and references therein, Langtjern 2002 from Larssen (2005) and references therein. Langtjern deposition is mean for the years 1988-92. See text for details. Units: meq/m^2/yr.

	Birkenes		**Langtjern**	
Deposition	Year 2018	Data source	Year 2002	Data source
Ca	13.0	proportional to Cl	4.2	proportional to Cl
Mg	31.5	proportional to Cl	2.6	proportional to Cl
Na	137.7	proportional to Cl	9.2	proportional to Cl
K	2.9	proportional to Cl	2.5	proportional to Cl
Cl	160.8	runoff flux	9.9	runoff flux
SO_4	43.8	runoff flux minus SO_4w	17.7	runoff flux minus SO_4w
SO_4^*	27.7	calculated	7.7	calculated
Ca^*	7.1	proportional to SO_4^*	2.8	proportional to SO_4^*
Mg^*	0.0	calculated	0.7	calculated
Na^*	0.1	calculated	0.7	calculated
K^*	0.2	calculated	2.3	calculated
BC^*	7.3	calculated	6.6	calculated
Weathering				
Ca	28	calibrated MAGIC	21.6	calibrated MAGIC
Mg	0	calibrated MAGIC	5.4	calibrated MAGIC
Na	20	calibrated MAGIC	5.5	calibrated MAGIC
K	2	calibrated MAGIC	0.1	calibrated MAGIC
SO_4w	20	estimated	0	estimated
BC_w	50	calibrated MAGIC	32.6	calibrated MAGIC
Net uptake (No harvest)				
BC_u	0	measured	0	scaled to Birkenes
N_u	0	measured	0	scaled to Birkenes
Net uptake (SOH)				
Ca	4.2	measured	1.6	scaled to Birkenes
Mg	1.1	measured	0.4	scaled to Birkenes
K	2.4	measured	0.9	scaled to Birkenes
BC_u	7.7	measured	3.0	scaled to Birkenes
N_u	5.2	measured	2.0	scaled to Birkenes
Net uptake (WTH)				
Ca	10.8	measured	4.2	scaled to Birkenes
Mg	2.6	measured	1.0	scaled to Birkenes
K	5.3	measured	2.1	scaled to Birkenes
BC_u	18.7	measured	7.3	scaled to Birkenes
N_u	23.6	measured	9.0	scaled to Birkenes
Nitrogen				
N_i	2.4	calculated	3.1	calculated
N_{de}	0	assumed	0	assumed

2.6 Site-specific ANC limits

In the Norwegian calculations of critical loads, the critical ANC concentration at which no adverse effects on biota occur, $[ANC]_{limit}$ was originally set to a constant, 20 µeq/l, based on surveys on fish in Norwegian lakes (Lien et al. 1996). (The square brackets [] denote concentrations rather than fluxes). This $[ANC]_{limit}$ gives a 95% probability of no damage to fish populations. Later, a variable $[ANC]_{limit}$ was introduced, based on the observation that for a given ANC there exist lakes of varying sensitivity. Conceptually, less sensitive systems should have a higher $[ANC]_{limit}$ since they will generally have a higher biological diversity, which requires a higher $[ANC]_{limit}$ to be held intact (Henriksen and Posch 2001). The variable $[ANC]_{limit}$ is termed $[ANC]_{limit,var}$ and is defined as:

$[ANC]_{limit,var} = k*Q*[BC^*]_o/(1+k*Q)$

where k is the proportionality constant describing the linear relationship between the $[ANC]_{limit}$ and the critical load, set to 0.25 yr/m, based on experience from the Nordic countries (for a critical load of 200 meq/m^2/yr the $[ANC]_{limit}$ should not exceed 50 meq/m^3), Q is the discharge m/yr and $[BC^*]_o$ is the sea-salt corrected pre-acidification base cation concentration. $[ANC]_{limit,var}$ has a range 0–50 µeq/l (if the expression gives a value higher than 50 µeq/l it is set to 50 µeq/l).

An additional adjustment to the $[ANC]_{limit,var}$ was introduced to take into account the effect of naturally occurring organic acids (Lydersen et al. 2004). Many Norwegian lakes are humic, and part of the organic acids will act as strong acid anions. An adjusted ANC, taking this contribution into account, gave a slightly better fit with fish status. The organic acid adjusted ANC is expressed as

$[ANC]_{oaa} = [ANC] – (1/3*m*[TOC])$

where 1/3 expresses that one third of the organic acids will be negatively charged in most natural waters, m is the site density (set to 10.2 µeq/mg C, according to Hruška et al. (2001)) and [TOC] is the total organic carbon concentration in mg C/l. The $ANC_{limit,oaa}$ which gave a 95% probability of no damage to fish populations (brown trout) was 8 µeq/l. However, rather than using this value, a combination of the two approaches is used as critical limit in the current calculation of organically adjusted critical loads:

$[ANC]_{limit,oaa,var} = k*Q*([BC*]_0\text{-}1/3*m*[TOC])/(1+k*Q)$

The range is adjusted to -13-40 µeq/l and the k to 0.2 yr/m due to the general downwards adjustment caused by the organic acid adjustment (Hindar and Larssen 2005).

Table 5. Constants and parameter values used to calculate the [ANC]limit,oaa,var.

	Units	**Birkenes**	**Langtjern**
k (for $ANC_{limit,var}$)	yr/m	0.25	0.25
k (for $ANC_{limit,oaa,var}$)	yr/m	0.2	0.2
Q	m/yr	1.15	0.60
[TOC]	mgC/l	5.2	9.6
m	µeq/mgC	10.2	10.2
$[ANC]_{limit,var}$	µeq/l	5.9	2.3
$[ANC]_{limit,oaa,var}$	µeq/l	2.1	-0.3

3 Results and discussion

3.1 Simulation of forest management scenarios with MAGIC

The MAGIC model simulations for Birkenes in the SURFER project indicated that there is a significant pulse of acidification in streamwater following clearcutting (Valinia et al. In prep.). The strongest acidification effect lasts 3-4 years after clearcut and is caused by leaching of NO_3 (due to reduced N uptake and decomposition of logging residues) which is not fully compensated by available base cations and therefore is accompanied by H^+ and aluminium. After the NO_3 peak has ceased, ANC and pH are still at a lower level than before the clearcut and the recovery rate is slow due the removal of base cations by SOH and WTH. Over the short-term SOH gave a higher peak in NO_3 concentrations and thus lower ANC and pH as compared with WTH. But over the longer term after the NO_3 peak had passed, SOH had higher ANC and pH relative to WTH (Figure 2).

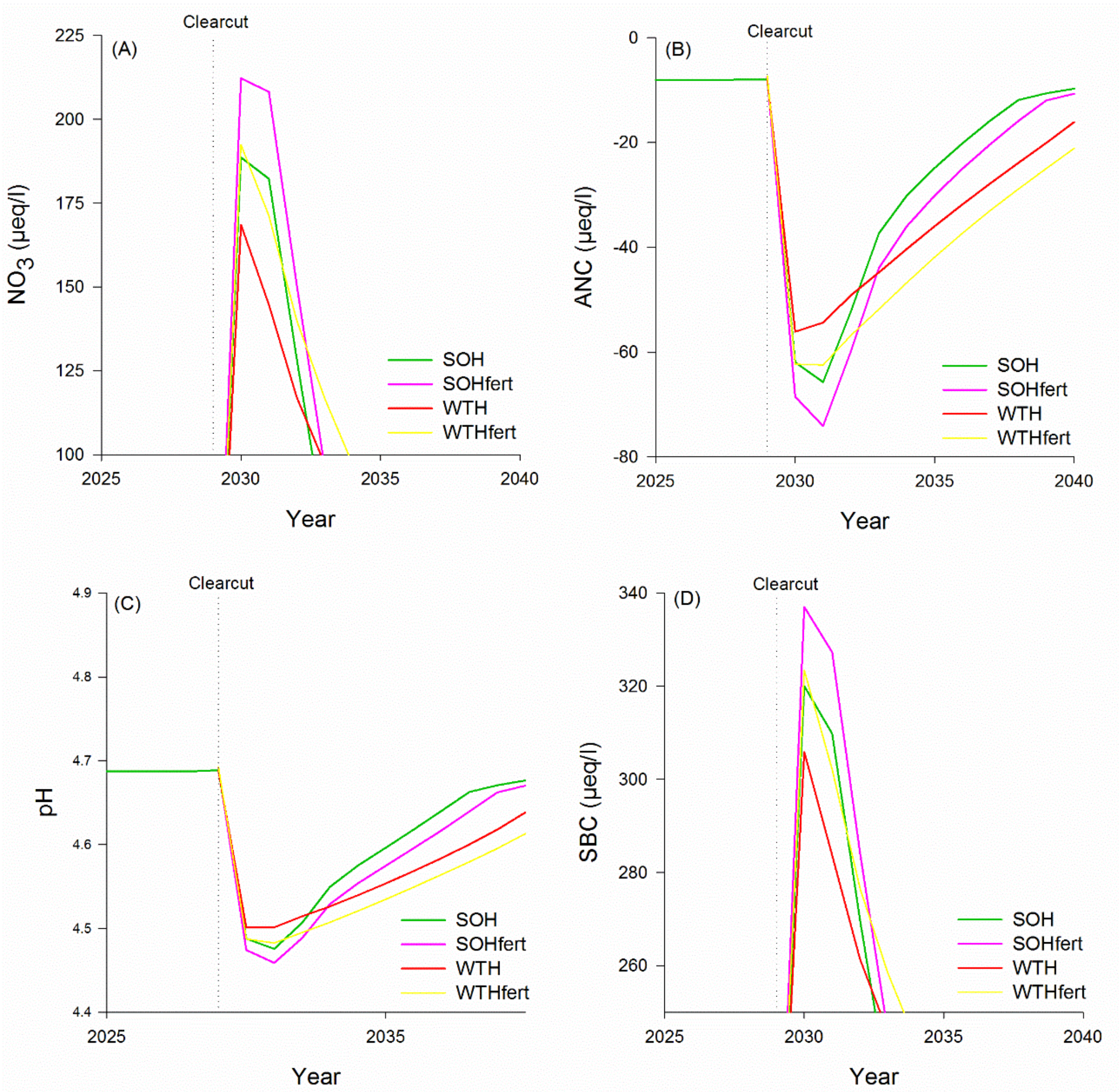

Figure 2. Results from the MAGIC simulations of several forest management scenarios at Birkenes. SBC: Soluble base cations. Shown are simulated concentrations of key surface water parameters for the period following clearcut in 2028. From Valinia et al. (In prep.).

The simulations indicated that fertilisation with 150 kgN/ha ammonium nitrate increased the height of the short-term NO_3 peak, in the case of SOH from simulated annual mean values of about 190 µeq/l to 215 µeq/l. This is again reflected in lower ANC and pH for the SOHfert scenario relative to SOH (Figure 2).

For the soil the simulations indicated substantial differences in the effect of WTH relative to SOH (Figure 3).

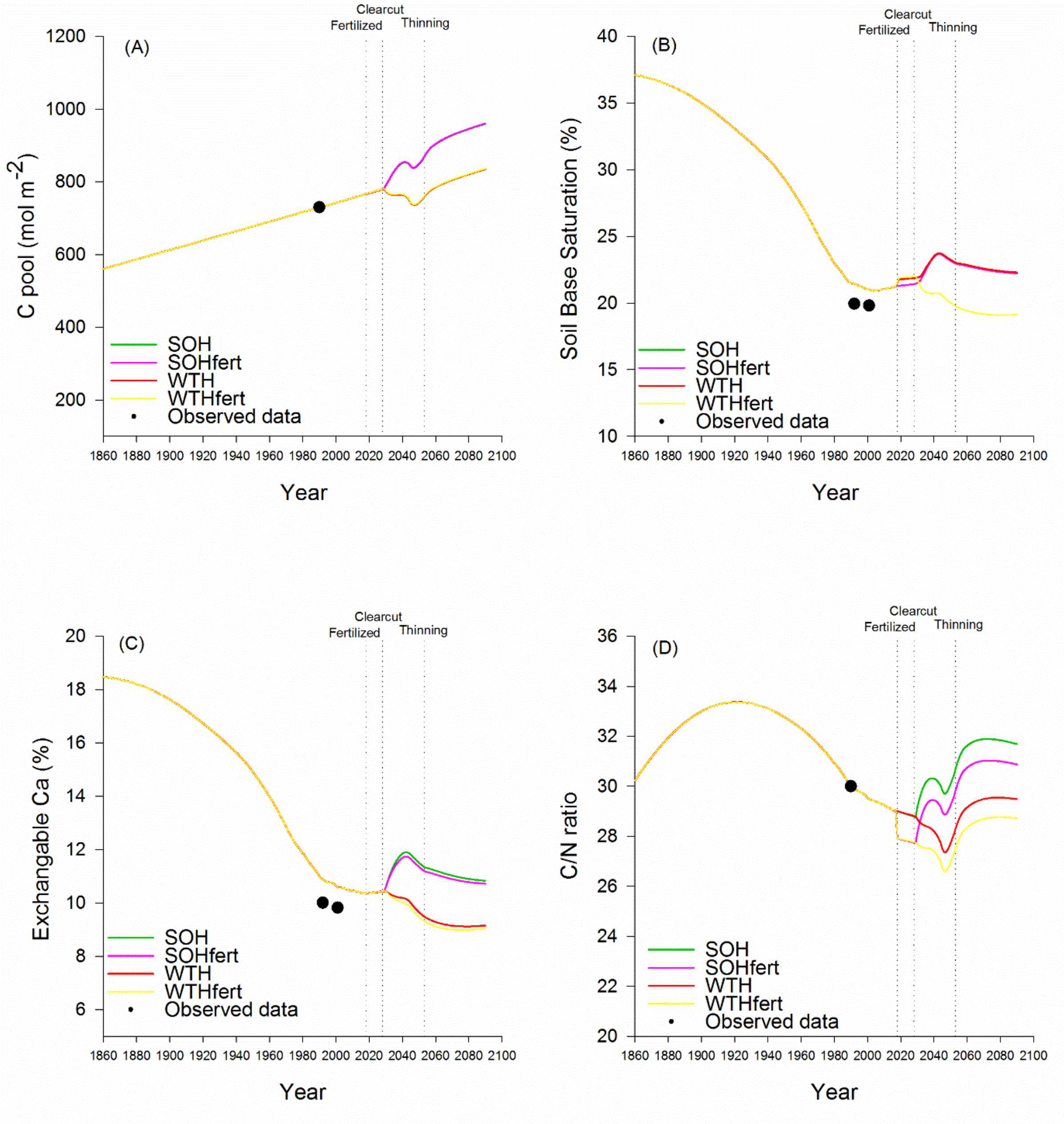

Figure 3. Results from the MAGIC simulations of several forest management scenarios at Birkenes. Shown are key concentrations of key soil parameters for the whole-time period (1860-2100) with four management methods and observed data (dots). Three major anthropogenic disturbances are highlighted by vertical dashed lines; 2018 forest fertilization; 2028 forest clear cut; 2054 forest thinning. In the upper panels the SOH and WTH lines are hidden behind the SOHfert and WTHfert lines, respectively. From Valinia et al. (In prep.).

WTH removes more carbon from the system (panel A), accelerates the depletion of the pool of base cations (panels B and C), and reduces the C/N of soil (panel D). The soil C pool is simulated to be about 15% lower following WTH relative to SOH. A lower pool of base cations in the soil implies that the ecosystem becomes more sensitive to acid deposition. Following WTH the soil base saturation is simulated to continue to decrease whereas in the SOH scenario the base saturation is simulated to increase. Thus, at Birkenes WTH entails continued soil acidification under present-day acid deposition whereas under SOH the soil begins to recover.

Forest fertilisation increased the amount of N in the soil, and thus lowered the C/N ratio in soil organic matter (Figure 3). This implies that the ecosystem may be slightly more susceptible to NO_3 leaching in the future.

3.2 Critical loads calculated with the SSWC and FAB models

The critical load equations are:
critical load of acidity: $CL(A) = BC^*_{dep} + BC_w – BC_u – ANC_{limit} – SO_4$ (weathering)
minimum critical load of N: $ClminN = N_i + N_u$
maximum critical load of N: $ClmaxN = CL(A) + N_i + N_u$

The calculations reveal that the differences in the critical loads for the various harvest scenarios are due entirely to the differences in uptake (i.e. removal) rates for base cations and nitrogen (Table 6, Figure 4). The critical load for acidity is lower at Birkenes than at Langtjern due to the higher growth rate of the forest and thus higher uptake rates of base cations.

Table 6. Critical loads for acidity (S and N) and N calculated by the SSWC and FAB models, respectively, for Birkenes and Langtjern, given no harvest and two forest harvest scenarios with and without forest fertilisation. Units: meq/m^2/yr.

Birkenes							SSWC			FAB	FAB
	BC*dep	+ BCw	- BCu	- ANClimi	- SO4 (weathering)		Cl (A)	Ni	Nu	ClminN	ClmaxN
No harvest	7.3	50	0	5.9	20		31.4	2.43	0	2.43	33.8
SOH	7.3	50	7.68	5.9	20		23.7	2.43	5.22	7.7	31.3
WTH	7.3	50	18.7	5.9	20		12.7	2.43	23.26	25.7	38.3
SOHfert	7.3	50	7.75	5.9	20		23.6	2.43	5.26	7.7	31.3
WTHfert	7.3	50	18.8	5.9	20		12.6	2.43	23.31	25.7	38.3

Langtjern							SSWC			FAB	FAB
	BC*dep	+ BCw	- BCu	- ANClimi	- SO4 (weathering)		Cl (A)	Ni	Nu	ClminN	ClmaxN
No harvest	6.6	32.6	0	2.9	0		36.3	3.1	0.0	3.1	39.4
SOH	6.6	32.6	2.99	2.9	0		33.3	3.1	2.0	5.1	38.4
WTH	6.6	32.6	7.3	2.9	0		29.0	3.1	9.0	12.1	41.2
SOHfert	6.6	32.6	2.99	2.9	0		33.3	3.1	0.0	3.1	36.4
WTHfert	6.6	32.6	0.0	2.9	0		36.3	3.1	0.0	3.1	39.4

The FAB critical load diagrams show that forest harvest practice entails a trade-off (Figure 4). At Birkenes WTH leads to substantially lower critical loads for acidity (from 24 to 13 meq/m^2/yr) due to increased removal of base cations in the harvested biomass and thus lower base cation pools in the soil. But WTH also leads to higher critical load for N (from 31 to 38 meq/m^2/yr) due to the extra N removed in the tops and branches and thus lower pool of N in the soil with less N available for leaching to streamwater. For Langtjern the differences between the critical loads calculated for the

SOH and WTH scenarios are much smaller due to the lower forest productivity. The critical load lines in the FAB model diagrams cross with SOH having higher CL(S) but lower CL(N) relative to WTH (Figure 4).

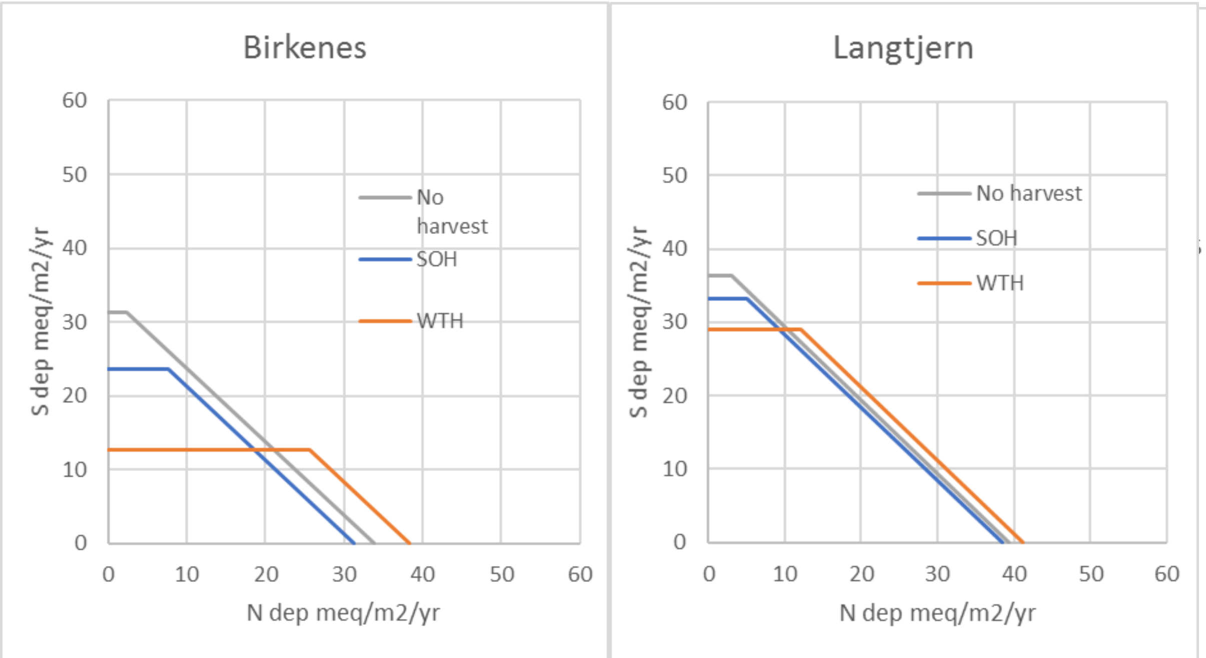

Figure 4. Critical load diagrams for Birkenes and Langtjern given no harvest and two forest harvest scenarios, stem-only harvest (SOH) and whole-tree harvest (WTH).

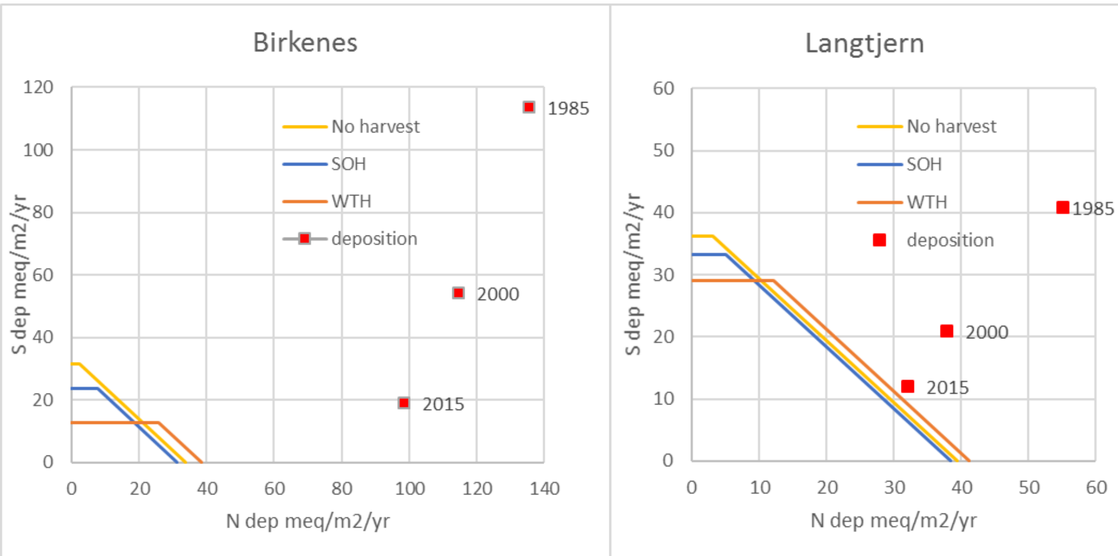

Figure 5. Critical loads and deposition of S and N for Birkenes and Langtjern given no harvest and two harvest scenarios, stem-only harvest (SOH) and whole-tree harvest (WTH). Deposition values are 5-year means estimated from streamwater fluxes (see text for details).

3.1 Exceedances in 1985, 2000 and 2015

At both Birkenes and Langtjern the differences in critical loads given the various forest harvest scenarios are small relative to the historical long-term changes in deposition of S and N, but significant in that future additional reductions in S deposition will probably be small (Figure 5).

At Birkenes deposition of both S and N greatly exceeded the critical load in the 1980s but the large decrease in S deposition over the past 30 years means that the S deposition is now about equal to the critical load (i.e. no exceedance for S). As future reductions in S deposition are likely to be minor, the lower CL for S under WTH implies that in the future with WTH S deposition may again exceed the critical load. Recovery from acidification may stop and re-acidification might occur. N deposition still far exceeds the critical load for N, regardless of harvest practice in the future. This implies that there is still a risk of N saturation in the future with increased leaching of NO_3 accompanied by lower ANC and lower pH.

At Langtjern the picture is somewhat different. Langtjern receives less acid deposition, and forest growth is much slower. As at Birkenes, the data for Langtjern indicate that the critical load both for acidity and N were exceeded in the 1980s, but by the year 2015 deposition of both S and N had decreased sufficiently such that the critical load was only slightly exceeded (Figure 5). Deposition of S was well below the critical load of S. Retention of N deposition at Langtjern is much greater than the long-term immobilisation rate, i.e. the system is not N saturated. Thus the current deposition of S and N to the ecosystem is so small that it no longer acts to acidify the surface water – the ecosystem is recovering. If N saturation occurs in the future, however, the ecosystem will again be threatened by acidification. At Langtjern the choice of forest harvest practice in the future appears to have little effect on the critical load for N.

3.2 Implication of different forest management regimes

This modelling study indicates that a change in forest harvesting intensity can significantly decrease the critical load of acidity for surface waters in acid-sensitive areas, leading to a higher sensitivity to acid deposition. The impact on critical loads, however, will depend on site-specific factors such as forest productivity and soil properties. The two case studies here represent two points along a range of forest productivity, acid-sensitivity and deposition.

S deposition in southern Norway has decreased substantially since the peak in the late 1970s. Nevertheless, in the period 2012-16 critical loads of acidity in surface waters were still exceeded in 7% of Norway (based on the SSWC model) and critical loads of N in 19% (based on the FAB model) (Austnes et al. 2018). Large-scale increases in forest harvesting at sites where critical loads are low or exceeded because of S deposition are likely to have a substantial impact on surface water acidification. Upscaling to forests in all of southern Norway will require national datasets for key site parameters.

Many other forest practices can potentially also affect the critical loads of acidity and nitrogen. Shorter rotation times, change in species, and afforestation can all be expected to affect the uptake rates of base cations and N and thereby alter the soil base saturation and C and N pools. Biogeochemical understanding and modelling results such as these from Birkenes and Langtjern suggest that forestry practices that entail increased rates of biomass removal will in general result in lower critical loads for acidity in surface waters. The risk of acidification will be greatest at sites that are by nature acid-sensitive and lie in areas currently receiving levels of acid deposition exceeding the critical load.

The combination of high forest productivity and high acid sensitivity is most common in southeastern and southernmost Norway. If forest harvest practices are changed toward increased removal of biomass, deposition of S to these areas must be decreased further to protect freshwater biota.

Increased forest harvesting depletes the soils of base cations, and thus will also potentially lower the critical load for acidity to forest soils. This aspect was not quantified here. In Norway, the critical load of acidity is generally lower for surface waters than for forests.

Increased forest harvesting removes progressively more N from the ecosystem in the harvested biomass, and thus the ecosystem can immobilise more N deposition before reaching the state of “N saturation”, the situation in which the leaching of inorganic N (mostly as NO3) increases above background levels. Increased forest harvesting thus entails a trade-off – the system can tolerate less S deposition, but more N deposition.

The modelled scenarios represent a worst case by assuming that 100% of the catchment forest was affected, either by stem-only or whole-tree harvest. In practice conventional harvesting techniques do not cut 100% of the forest in a catchment. In addition, it is mandatory to establish buffer strips along streams with permanent flow throughout the year.

Nevertheless, transition to greater biomass removal, with stem-only and especially whole-tree harvest, will result in a long-term depletion of soil base cations with potential re-acidification of surface waters, unless further reductions in acid deposition are achieved. The effects will be most pronounced in small streams close to the clearcut forest and will gradually decrease as the water moves downstream in a river network.

To avoid unwanted acid episodes and potentially harmful effects on freshwater biota, it is important to carefully consider surface water’s sensitivity to acidification when planning forest fertilisation measures and choose between harvesting methods.

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