

Modelling the role of nitrogen in
acidification of Swedish lakes:
future scenarios of acid
deposition, climate change and
forestry practices

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Summary

There are three major drivers that can cause future changes in lake water chemistry: air pollution, land use and climate change. In this report we used an extensive set of Swedish lakes sampled in 1995, 2000 and in 2005 to model future lake water chemistry under 5 different scenarios. The base case scenario represented deposition of air pollutants under current legislation (CLE); that is assuming that emissions of sulphur (S) and nitrogen (N) will be reduced as currently agreed by the Gothenburg protocol, NEC directive and other legislation. After the agreed emission reductions were achieved, no further reduction in deposition was assumed and deposition was maintained constant up to year 2100. The base scenario assumed no change in current forestry practices and no climate change. A second other deposition scenario was based on maximum (technically) feasible emission reduction (MFR). The MFR scenario also did not assume change of either forestry practices or climate. A maximum biomass harvest was modelled (land use, LU, scenario), which entailed harvest of tree stems, slash and stumps. A scenario of climate change (CC) followed the IPCC A2 scenario downscaled to Sweden by SMHI. Finally climate change and land use were combined (CCLU scenario). The CC, LU and CCLU scenarios were driven by the “current legislation” (CLE) deposition scenario for S and N deposition. The biogeochemical model MAGIC was used in this project, and scenarios were evaluated up to year 2100. Special attention was paid to the impact of the future scenarios on N leaching.

By the year 2010 almost all the chemical recovery expected under the CLE emission scenario for S and N will have occurred, and no further improvements in lake water chemistry can be expected unless new reductions in S and N emissions are forthcoming. The results for the MFR scenario clearly show that there is room for further improvement of lake chemistry if reductions are reduced beyond 2010 levels. Under the CC, LU and CCLU future scenarios, the results suggest that recovery from acidification will stop, and the majority of the lakes will decline in ANC over the next 90 years. Much of this decline is apparently due to increased flux of N from catchment soils to surface waters, due to the simulated increased rate of decomposition of soil organic matter. Both the increased removal of biomass and climate change are expected to increase the decomposition rate; the first due to disturbance of forest soil, and the second due to increased soil temperature. Carbon from the decomposed soil organic matter is assumed to be released to the atmosphere as CO₂. The N released from soil to water will have an acidifying effect on lakes and streams and also increase the nutrient load to coastal marine ecosystems in the Baltic Sea and Skagerrak. These results can also be used to make a rough estimate of the effect of climate change and increased biomass removal from the forest on the C budget for the Swedish forest soils. For the CC, LU and CCLU scenarios, respectively, the soil C pool is expected to decrease from year 2010 to year 2100 by 8%, 17% and 25% respectively. These values work out to be 7, 16, and 23 Mt CO₂/yr, and can be compared with the total anthropogenic CO₂ emissions for Sweden of 53 Mt CO₂ in 2004.

Table of Contents

Summary	1
Abbreviations and explanations	3
1 Introduction	5
2 Data sources, materials and methods.....	7
2.1 The MAGIC Model.....	7
2.2 List of required data.....	8
2.3 Preparation of input data files.....	11
2.4 Assumptions for modelling.....	12
2.5 Calibration setup	13
2.6 Scenario descriptions.....	14
3 Results	21
3.1 Calibration.....	22
3.2 Comparison of the present-day status for the 348 subset and 1151 library lakes	26
3.3 Time tracks for example lakes.....	29
3.4 Future changes in lake chemistry.....	31
3.5 Future changes in soil chemistry.....	40
4 Discussion	43
5 Acknowledgements	45
6 References	45

Abbreviations and explanations

ANC	acid neutralising capacity, defined as equivalent sum of base cations less equivalent sum of strong acid anions
ASTA base	International and National Abatement Strategies for Transboundary Air Pollution future scenario with no change in future climate, no change in future forest management
BC	base cations, Ca ²⁺ , Mg ²⁺ , Na ⁺ , K ⁺
BS, %BS	soil base saturation
C	carbon
Ca	calcium
CC	future scenario with maximum change in future climate, no change in future forest management
CCE	Coordination Centre for Effects, part of ICP M&M
CCLU	future scenario with maximum change in future climate, maximum utilisation of the forest
CEC	cation exchange capacity
Cl	chloride
CLE	current legislation
CLIMEX	Climate change experiment (Norway)
CO ₂	carbon dioxide
DIN	dissolved inorganic N
DOC	dissolved organic carbon
DON	dissolved organic N
ECHAM	European Centre Hamburg Model (global climate model)
EMEP	European Monitoring and Evaluation Programme, part of UN-ECE LRTAP convention
FAB	First-order Acidity Balance model
GCM	Global Circulation Model
ICP M&M	International Cooperative Programme for Modelling and Mapping, part of UN-ECE LRTAP convention
IPCC	United Nations Intergovernmental Panel on Climate Change
LRTAP	Long-Range Transboundary Air Pollution, convention under the UN-ECE
K	potassium
K _{Al} (log ₁₀)	Dissociation constant for aluminium hydroxide solid phase
LTSP	North American Long-Term Soil Productivity experiment
LU	future scenario with no change in future climate, maximum utilisation of the forest
MAGIC	Model of Acidification of Groundwater In Catchments
MFR	maximum (technically) feasible emission reduction
Mg	magnesium
N	nitrogen
N ₂	nitrogen gas
N ₂ O	nitrous oxide
N ₂ O ₂	dinitrogen dioxide
Na	sodium
NEC	National Emission Ceilings directive, EU

NFI	Swedish National Forest Inventory
NH ₄ ⁺	ammonium
NH _y	reduced nitrogen species
NO ₂ ⁻	nitrite
NO ₃ ⁻	nitrate
NO _x	oxidised nitrogen species
pCO ₂	partial pressure of CO ₂
pK	dissociation constants for organic acids
RCM	Regional Climate Model
S	sulphur
SBC	sum of base cations, Ca ²⁺ , Mg ²⁺ , Na ⁺ , K ⁺
SK	Swedish Survey on Forest Soils and Vegetation (Ståndortskartering)
SLU	Swedish University of Agricultural Sciences
SMHI	Swedish Meteorological and Hydrological Institute
SO ₄ ²⁻	sulphate
SO ₄ [*]	sea salt corrected sulphate concentration
Swedish EPA	Swedish Environmental Protection Agency (Naturvårdsverket)
TIN	total inorganic nitrogen
UN-ECE	United Nations Economic Council for Europe

1 Introduction

Leaching of nitrogen (N) can cause acidification and eutrophication of surface waters. In unpolluted natural and semi-natural ecosystems such as forested and upland areas of Sweden, typically almost the entire N in surface waters is as dissolved organic N (DON). DON leaching does not cause acidification of soils or surface waters. Chronic deposition of inorganic N compounds from the atmosphere can cause increased leaching of dissolved inorganic N (DIN) from natural and semi-natural ecosystems (Aber et al. 1989). Nitrate (NO_3^-) typically dominates leaching of DIN, while the concentrations of other two most common inorganic N species, ammonium (NH_4^+) and nitrite (NO_2^-), are much lower. Use of fertilizers in agriculture can cause N leaching in all forms and $\text{NH}_4\text{-N}$ leaching could even be dominant. Runoff from municipal and industrial wastewaters can also cause increased concentrations of DIN. Deposition of inorganic N compounds may cause increased DON leaching, but this has not been sufficiently studied (Molot and Dillon 1993, Dillon et al., 2009).

Mass balance calculations indicate that forest soils over all of Sweden currently accumulate nitrogen deposited from the atmosphere (Akselsson 2005). In the southern part of Sweden N deposition is in excess of combined N losses from forest ecosystems due to harvesting the forest and nitrogen leaching to ground- and surface waters. It is uncertain how long the N accumulation in soils will continue without an onset of an increase in N leaching to surface waters. It has been shown that disturbance such as clear-cut, ploughing, stump harvesting, fire and wind storm felling can stimulate accelerated decomposition of soil organic matter and consequently strongly increased leaching of N and other solutes (Vitousek et al. 1979, Aber et al. 2002, Houlton et al. 2003).

Forests are increasingly being looked to as a source of renewable energy. Traditional forest practice usually entails removal of the boles of the trees only, with the branches and foliage left on site. Greater extraction of biomass from forests might entail use of whole-tree harvesting, or even removal of the stumps and organic-rich upper soil layers. Removal of biomass and disturbance of the soil causes changes not only in the carbon (C) stocks (Figure 1) of the ecosystem but of the associated N and base cations in the biomass and soil (Rosen and Lundmark-Thelin 1987, Ohlsson et al. 1996, Powers et al. 2005). This in turn affects the chemical composition of runoff (Neal et al. 1992, Rosen et al. 1996) and potentially the acidification and eutrophication of surface waters (see also BIOGEMON Abstracts 2009 Clarke et al. p. 466, for biomass removal effects in Norway; Göttlein et al. p 467 for nutrients pools under different forest harvest practices in Germany; Hazlett and Fleming, p. 468 and Hazlett p. 469 for overview; Hellsten et al. p. 470 for Sweden; Hruska et al. p. 471 for MAGIC, biomass removal in CZ; Vanguelova et al. p. 481 for UK).

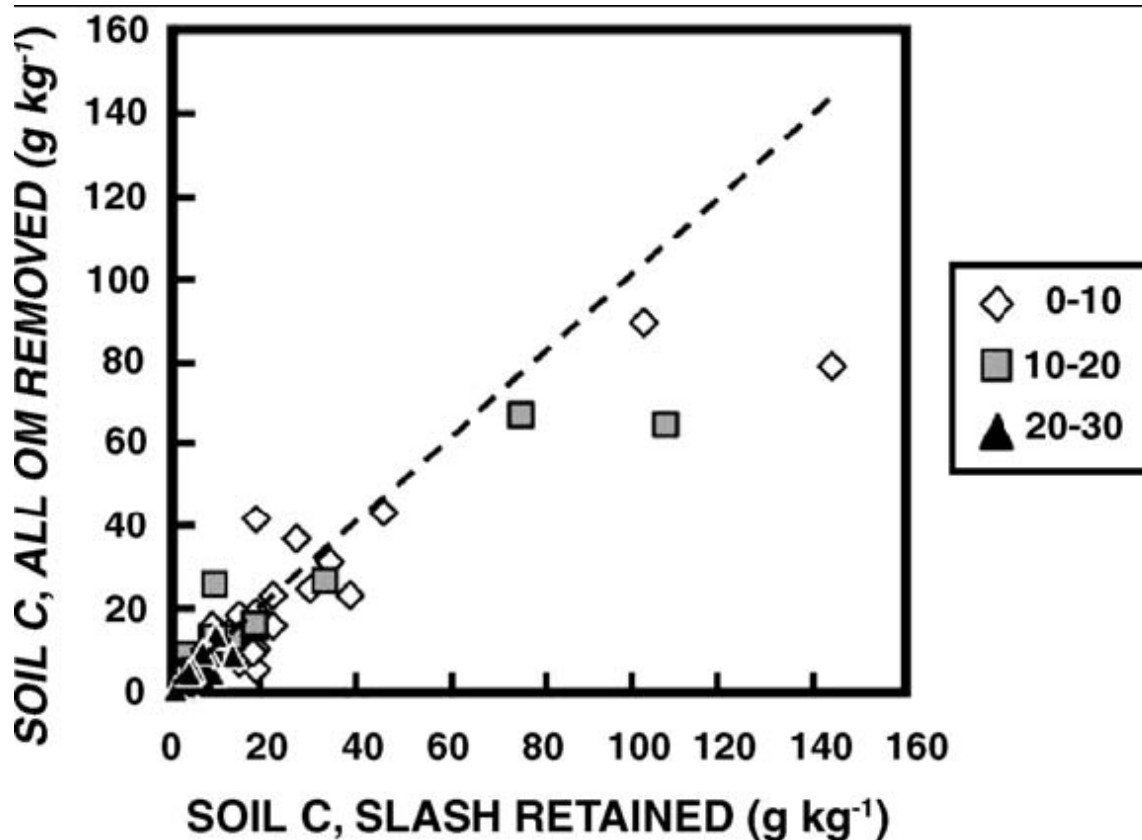


Figure 1. Concentration of organic soil C at 10 years for three soils depths as influenced by slash retention or complete removal of all surface organic residues. Depths are indicated by symbols and each data point represents a replicated treatment plot. Basis: 21 LTSP installations in five states with complete data sets. Dashed line indicates 1:1 parity between treatments (from Powers et al. 2005).

Climate change will affect the C and N cycles in forested and other semi-natural ecosystems. Higher temperature will promote forest growth, with faster extraction of nutrients from the soil. Higher temperature might result in increased decomposition of soil organic matter with release of the associated N and base cations, such as was demonstrated experimentally in the CLIMEX experiment in Norway (Van Bremen et al. 1998). Changes in precipitation are also expected to change the concentrations of solutes leached from soils.

It is difficult to predict how the combination of continued N deposition, reduced S deposition with recovery from acidification, a changing climate, and increased use of forest biomass will affect the stability of soil organic matter (containing large quantities of accumulated N) and consequently the future acidification status of lakes and streams.

In November 2007 the Coordination Centre for Effects (CCE) of the International Cooperative Programme for Modelling and Mapping (ICP M&M, part of the UN-ECE LRTAP Convention) issued a call for data for results from application of dynamic models to soils and surface waters given several specified future scenarios of sulphur (S) and nitrogen (N) deposition. In response to this call, the dynamic model MAGIC (Model of Acidification of Groundwater In Catchments) (Cosby et al. 1985a, Cosby et al. 1985b, Cosby et al. 2001) was calibrated to a dataset of 1218

Swedish lakes to project future acidification of surface waters in Sweden given alternative scenarios of future S and N emissions in Europe (Hettelingh et al., 2008).

We used the MAGIC model together with data from the 1218 Swedish lakes to assess the relative effect of alternative possible future combined scenarios of forest management and climate on soils- and lake water acidification in Sweden. A matrix of future forest management and climate scenarios was designed to cover four hypothetical future forest management and climate change combinations which span from present-day “business as usual” (no change in either forest management and climate change) to “worst case” (most extensive biomass harvesting forestry practice in combination with largest climate change). All four scenarios were driven by the “current legislation” (CLE) deposition scenario for S and N deposition. Posch et al. 2009 have made a similar evaluation for lakes in Finland. A fifth scenario modelled in this project was a decrease of deposition beyond the current legislation emissions, the so called MFR (Maximum Feasible Reduction) scenario. The MFR scenario did not involve any change in climate or forestry practices.

2 Data sources, materials and methods

2.1 The MAGIC Model

The dynamic model MAGIC was used to calculate future acidification status (as measured by acid neutralising capacity ANC) for the Swedish lakes. MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on soils and surface water chemistry (Cosby et al. 1985a, 1985b, 2001). The model simulates soil solution chemistry and surface water chemistry to predict the annual average concentrations of the major ions in lakes and streams. MAGIC represents the catchment with aggregated, uniform soil compartments (one or two) and a surface water compartment that can be either a lake or a stream. MAGIC consists of (1) a section in which the concentrations of major ions are assumed to be governed by simultaneous reactions involving sulphate adsorption, cation exchange, dissolution-precipitation-speciation of aluminium and dissolution-speciation of inorganic and organic carbon, and (2) a mass balance section in which the flux of major ions to and from the soil is assumed to be controlled by atmospheric inputs, chemical weathering inputs, net uptake in biomass and losses to runoff. At the heart of MAGIC is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from this pool change over time owing to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry. The degree and rate of change in surface water acidity thus depend both of flux factors and the inherent characteristics of the affected soils.

The soil layers can be arranged vertically or horizontally to represent important vertical or horizontal flowpaths through the soils. If a lake is simulated, seasonal stratification of the lake can be implemented. Time steps are yearly or monthly. Time series inputs to the model include annual or monthly estimates of (1) deposition of ions from the atmosphere (wet plus dry deposition); (2) discharge volumes and flow routing within the catchment; (3) biological production, removal and transformation of ions; (4) internal sources and sinks of ions from weathering or precipitation reactions; and (5) climate data. Constant parameters in the model include physical and chemical characteristics of the soils and surface waters, and thermodynamic constants. The model is calibrated using observed values of surface water and soil chemistry for a specific period.

MAGIC has been modified and extended several times from the original version of 1984. In particular, organic acids have been added to the model (version 5; (Cosby et al. 1995)) and most recently nitrogen processes have been added (version 7; (Cosby et al. 2001)).

The MAGIC model has been extensively applied and tested over the past 20 years at many sites and in many regions around the world (Cosby et al. 2001). More than 500 peer-reviewed articles in the international scientific literature have cited the original MAGIC publication. Overall, the model has proven to be robust, reliable and useful in a variety of scientific and environmental management activities (Cosby et al. 1995, Ferrier et al. 1995, Jenkins et al. 1998, Wright et al. 1998, Posch et al., 2008). Recently MAGIC was used to assess the recovery of European surface waters given the CLE (Gothenburg protocol and other agreed legislation) deposition scenario (Wright et al. 2005).

2.2 List of required data

The data required to run MAGIC (Figure 2) were spatially and temporally averaged (or ‘lumped’) to represent the whole catchment area (divided into one soil and one surface water compartment) and the time step of the model (annual). The observed physical and chemical data for each lake and its catchment were assumed to be representative of the lake and its catchment at that time step. Any uncertainty in these data and in the representativeness is incorporated into the model and the prediction must be interpreted accordingly. The data assumed constant over the calibration period, i.e. hindcast, required for calibration at each lake are given below:

Hydrological parameters:

- Annual runoff (m/yr)
- Annual precipitation (m/yr)

Soil parameters:

- Soil depth (m)
- Porosity (%)
- Bulk density (kg/m³)
- SO₄ maximum adsorption capacity (meq/kg)
- SO₄ half-saturation coefficient (meq/m³)
- Dissociation constant for aluminium hydroxide solid phase, K_{Al} (log₁₀)
- Temperature (annual average) (°C)
- pCO₂ (%)
- Organic acids (mmol C/m³)
- Dissociation constants for organic acids (pK)
- Nitrification (% of input)

Forest parameters:

- % of catchment covered by forest
- Mean annual net uptake of Ca, Mg, K, Na, and N in biomass

Surface water parameters:

- Retention time (yr)
- % of catchment area occupied by lake
- Temperature (annual average) (°C)

- Dissociation constant for aluminium hydroxide solid phase, K_{Al} (log10)
- pCO_2 (%)
- concentration of organic acids (mmol C/m³)
- Dissociation constants for organic acids (pK)
- Nitrification (% of input)
- Mass transfer coefficient for NO_3 (m/yr)
- Mass transfer coefficient for NH_4 (m/yr)

Surface water and soil chemistry in calibration year (i.e. 2000):

- Lake concentration of major ions (Ca, Mg, Na, K, NH_4 , SO_4 , Cl, NO_3) (meq/m³)
- Soil cation exchange capacity (meq/kg)
- Soil exchangeable base cations (Ca, Mg, Na, K) (meq/kg)
- Soil pool of organic carbon (mol/m²)
- Soil pool of organic nitrogen (mol/m²)

Deposition parameters in calibration year (i.e. 2000):

- Flux (wet and dry) of major ions (Ca, Mg, Na, K, NH_4 , SO_4 , Cl, NO_3)

The changes in soil and lake chemistry over time during the calibration period (from the assumed pre-pollution steady-state condition in 1860 to the calibration year of 2010) are assumed driven by changes in deposition of major ions from the atmosphere and any changes in net uptake of base cations and nitrogen by the forest. The time sequence of change in these two fluxes must thus be specified at an annual time step for the calibration period (1860-2010).

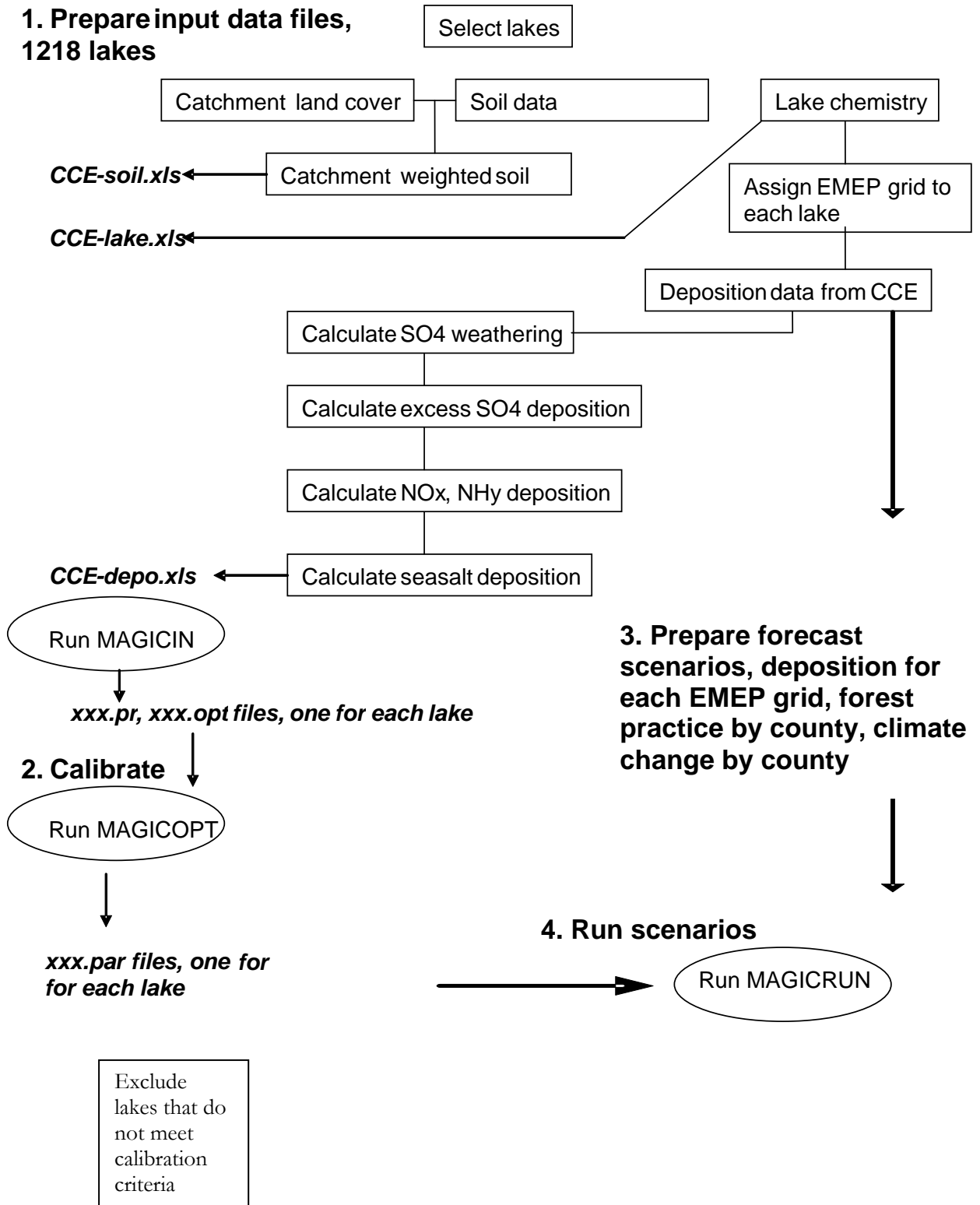


Figure 2. Schematic flow diagram showing sequence of tasks carried out to calibrate MAGIC and run the scenarios for future deposition, forest management practices and climate change for the 1218 lakes in Sweden in this study.

2.3 Preparation of input data files

The lakes were sampled in 1995, 2000 and 2005 as part of national surveys of lakes (Riksinventeringen). Description of the monitoring program and lake chemistry data are available from the Swedish University of Agricultural Sciences, SLU, (www.ma.slu.se). Lake annual runoff and lake catchment land use characteristics were obtained from SLU (Jens Fölster pers. comm.)

Forest soil data came from the Swedish Survey on Forest Soils and Vegetation (SK) 1983-87, which is a regularly-repeated survey of forest vegetation and soil chemical and physical qualities, at the permanent plots of the Swedish National Forest Inventory (NFI). Data are downloadable from www-markinfo.slu.se. These were aggregated up (arithmetic averages weighted by soil mass) for each lake catchment. For each lake catchment an average soil properties from the nearest 1 – 20 soil samples were lumped together to represent catchment soil. On average 11 nearest soil samples per catchment were used. The distance of relevant samples from the lake increased from south to north and was estimated for each lake according to procedure described by Moldan et al., (2004). In the absence of a national soil inventory of soils in non-forested land we were relegated to assigning from data available from various research projects. This problem was most obvious at lakes with zero percentage forest cover and therefore no forest soil sampling points in their catchments. For those catchments we assigned an average soil properties determined by soil sampling at two areas in Norrbottens county (Svarén, 1996).

Base cation uptake (actually annual net accumulation in biomass) was assumed to be zero for non-forested areas. For forests we used region and forest type specific uptake rates as calculated by the ASTA program (Axelsson et al., 2006), weighted by the percent forest cover at each catchment.

Deposition in year 2005 was estimated for each lake catchment from the measured lake chemistry and the deposition modelled for EMEP squares 50x50 km provided by CCE. First SO₄ deposition was calculated. The sources for SO₄ in lakewater were assumed to be comprised of (1) weathering of soil minerals or release from lake sediment, (2) deposition of seasalts, and (3) anthropogenic SO₄. Seasalt SO₄ was assumed to equal 0.103 Cl (ratio of these ions in seawater). SO₄ from weathering was assumed zero in all cases where excess SO₄ deposition calculated from the lake water chemistry and discharge was up to twice as high as average difference between the two fluxes (in 2005). In other words S weathering was assumed zero at all lakes where runoff SO₄ flux was below upper thin line in Figure 3. In cases where calculated excess SO₄ deposition was above the upper acceptable difference between EMEP and lake water flux, the weathering component was assumed to account for the part of S input above the average regression line between EMEP input and runoff output (thick black line in Figure 3).

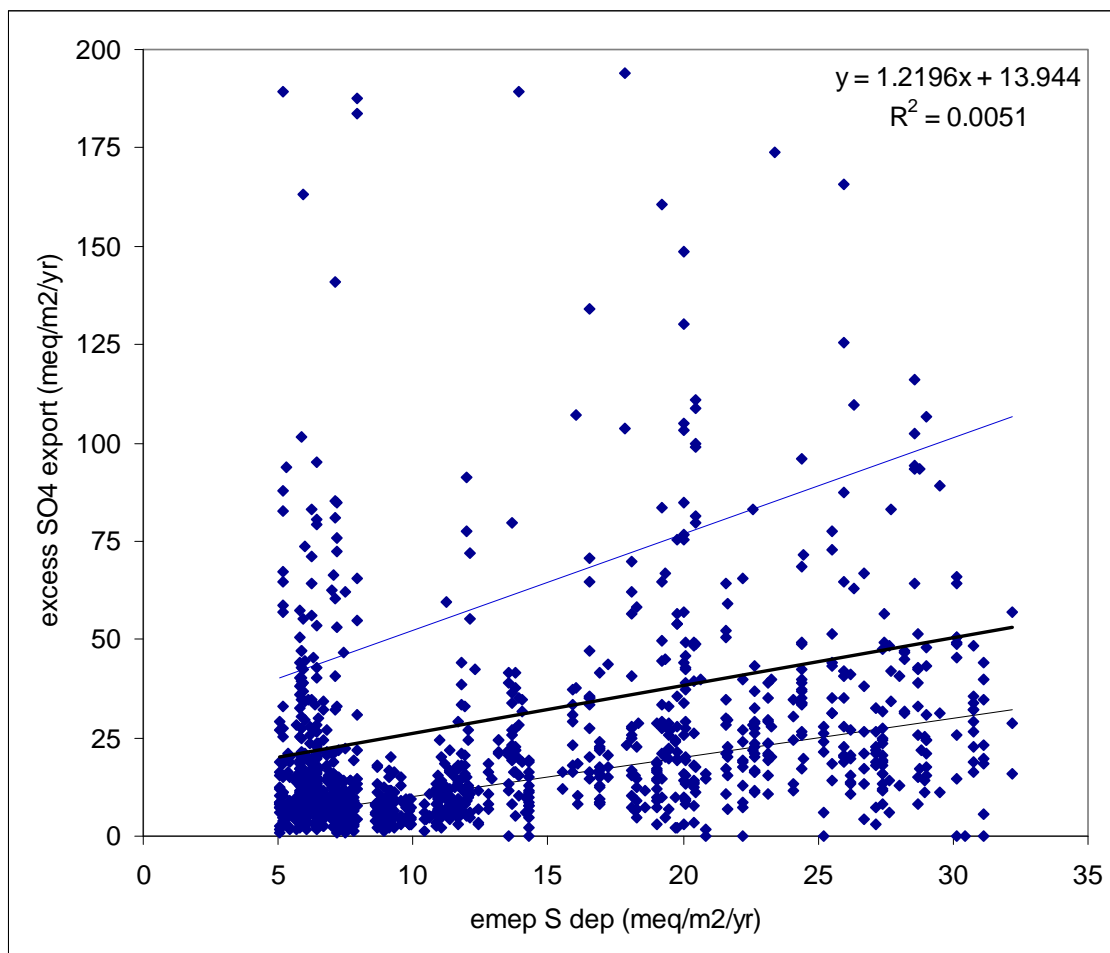


Figure 3. Runoff export of SO₄ (sea salt corrected) plotted against EMEP SO₄ deposition at corresponding 50x50 km EMEP square. Thick black line indicates average regression between EMEP input and lake water output. Lakes with output higher than twice the average regression slope (upper thin line) were assumed to have an internal source of SO₄ within the catchment, either from weathering or from lake sediment.

Deposition of NO_x and NH_y was then calculated from the anthropogenic SO₄ (above) and the ionic ratios in the deposition data (NO_x/SO₄, NH_y/SO₄) provided by the CCE. Deposition of Cl was assumed equal to the output flux at each lake (based again on concentration in lake water and discharge). The deposition of Na, Mg, Ca, K, and marine SO₄ were then calculated from the deposition of Cl and the ionic ratios of these ions in seawater. Deposition sequences for the “historical” period 1880–2010 were specified by the CCE for each EMEP50 grid square for the three components S, NO_x, and NH_y. The historical deposition values were normalised to the deposition values calculated for the year 2005.

2.4 Assumptions for modelling

Nitrogen: We assumed that the leaching of dissolved organic N (DON) from the catchment-lake system was unchanged by N deposition, forest practices and climate change. Further we assumed

that this DON was exactly compensated by fixation of atmospheric N and gaseous losses of N (as N₂, N₂O and N₂O₂) in the lake and its catchment.

Carbon: We assumed that for the hindcast (1860-2010) and under the base case future there were no net changes in the C pool of either the soil or of the below- and above-ground biomass.

Base cations: We assumed that the ecosystem was at steady-state in the pre-pollution starting year (1860), such that the sum of input of base cations (BC) to the system (deposition and weathering) exactly matched the sum of the output from the system (net uptake in biomass and loss by runoff).

Forest growth and harvest: In the hindcast we assumed that the net annual uptake of nutrients in the forest was equal to the amount removed from the ecosystem at harvest divided by the mean rotation length (yrs). The biomass removal from the land covered by forest was assumed to be as follows:

- 1860-1970 stems only
- 1970-2000 stems plus 30% of branches and foliage, the change ramped over this 30 year period
- 2000-2010 stems plus 30% of branches and foliage

2.5 Calibration setup

The work started with the statistically-selected 1218 lakes that had been used in conjunction with the CCE 2008 call for data. MAGIC had been calibrated to these 1218 lakes with N dynamics turned off. These calibrations did not use N dynamics, but rather assumed a constant percent retention of N in the catchment/lake system for each site.

For the new calibrations here (Figure 2) with N dynamics turned on, additional information was needed to setup the N dynamics at each site with respect to lakes and catchments soils.

Changes in model setup were as follows:

Lakes:

- the switch was turned on to activate the N dynamics option,
- the mass transfer coefficient for NO₃ was set to 5 m/yr (standard value used in European critical load calculations with the First-order Acidity Balance model FAB; see Henriksen and Posch 2001).
- The % nitrification was adjusted down from 100% such that the simulated NH₄ concentration matched the observed, or set to 0% if the simulated was less than the observed.

Soils:

- Added plant uptake of NO₃ based on % forest cover and productivity class at each site
- Nitrification set to 100%
- Added C decomposition set to 1% of the soil pool (intended for forecast scenarios only)

In the default parameter template the following changes were made:

- The range for the C/N curve was set to 10, i.e. the transition from 100% retention of inorganic N in the soils to 0% N retention occurs when C/N ratio drops from the upper limit by 10 units to the lower limit (Figure 9).

Historical sequences:

- Deposition sequences were the same as previously, supplied by CCE for each EMEP grid, scaled to year 2010 = 1
- Uptake sequences were the same as previously, these differ from south-to-north specified by county due to differences in forest productivity
- Add new sequence for runoff (held constant at 1 in hindcast)
- Add new sequence for CEC (cation exchange capacity) (held constant at 1 in hindcast)
- Add new sequence for N dynamics, plant uptake of NO₃ set the same as the sequence for BC, and decomposition of C (held constant at zero in hindcast)

The windows for the automatic calibration (optimiser programme MAGICOPT.EXE) were set to ± 2 $\mu\text{eq/l}$ for all the ions (match TIN in lake rather than NO₃ and NH₄ individually), ± 0.5 units for soil C/N, ± 0.2 units for % saturation of the four base cations. The limits for the optimised parameters were set to:

- weathering rates for each of the four base cations: 0 to 5000 meq/m²/yr
- the upper threshold of the C/N curve: 15 to 35
- initial C/N in 1860: 10 to 45

The optimiser sought to match the observed 2005 lake chemistry and the 1995 observed soil chemistry and the hindcast was run to the year 2010.

2.6 Scenario descriptions

Four future scenarios were set up and the model run for the period 2010 -2100. All four scenarios were driven by the “current legislation” (CLE) deposition scenario for S and N deposition. Values for these were obtained from the CCE and specified for each of the 50X50 km EMEP grids in Sweden. The CLE projects only slight decreases in S and N deposition in the future from the levels in 2010. In addition a fifth scenario was run with a lower S+N deposition scenario, maximum feasible reduction (MFR), in the future. Deposition sequences for S and N were developed specifically for each lake using the shape of EMEP deposition scenario at nearest 50x50 grid square and actual deposition at each lakes catchment. An example of deposition sequences from 1860 to 2100 is given for two lakes in Figure 4.

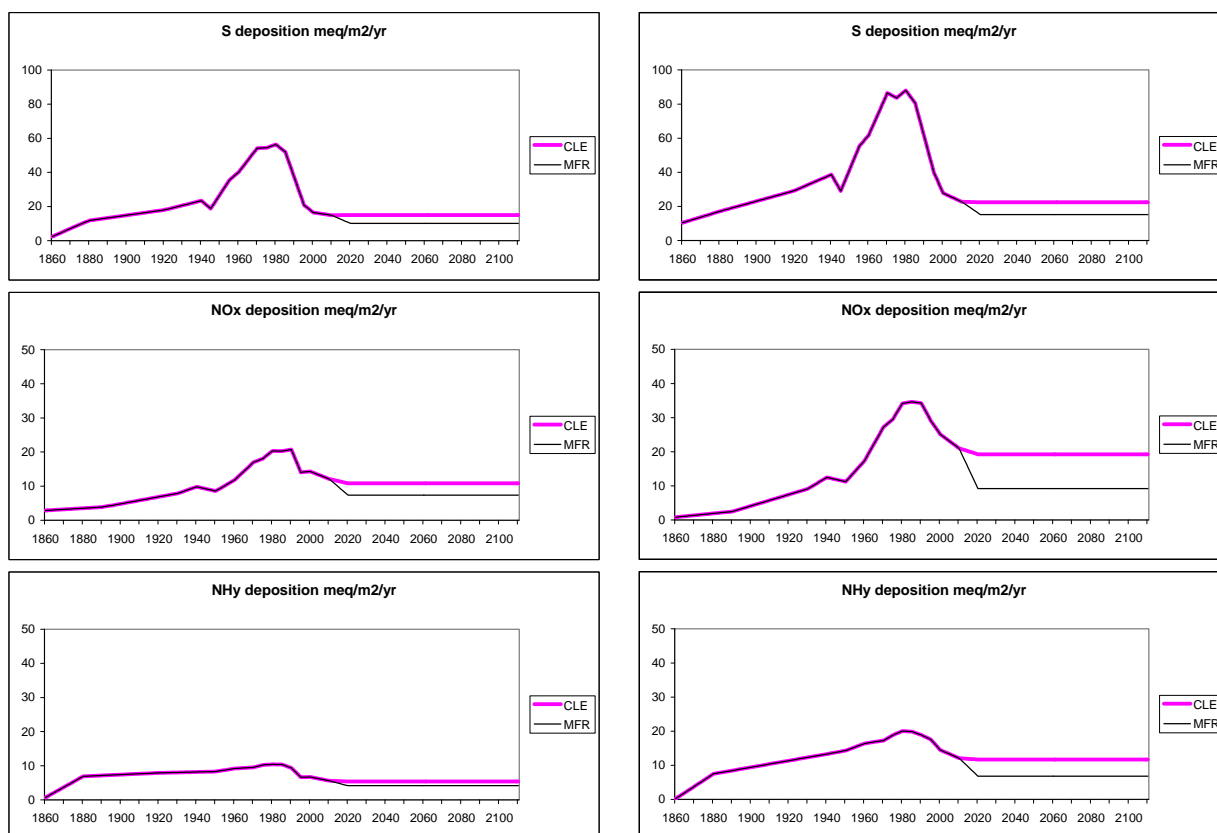


Figure 4. S and N (NO_x =oxidised N species; NH_y = reduced N species) deposition histories and future scenarios for two lakes in this study. Left-hand panels: site BD291 (Norrbottens län, northern Sweden); right-hand panels: site O077 (Västra Götalands län, southern Sweden). CLE= current legislation; MFR=maximum feasible reduction. The histories and scenarios were supplied by the CCE, and scaled here such that the simulated match the observed SO_4 concentrations in lakewater in year 2005 (see text for details).

The matrix of four scenarios (Figure 6) of forest management and climate change were defined as follows:

- Scenario base (no change in future climate, no change in future forest management).
- Scenario LU (no change in future climate, maximum utilisation of the forest)
- Scenario CC (maximum change in future climate, no change in future forest management)
- Scenario CCLU (maximum change in future climate, maximum utilisation of the forest)

		Climate change	
		None	maximum
Biomass use	Stems only	base	CC
	Stems, slash and stumps	LU	CCLU

Scenario base.

This scenario is the base case, in which neither forest harvest or climate is changed from conditions in the year 2010, and the lake-catchment ecosystem is affected only by the changes in the future deposition of S and N under the CLE scenario.

Scenario LU.

Maximum utilisation of biomass in the forest, but no climate change, CLE deposition scenario for S and N deposition. Forest harvesting affects the chemical and physical properties of the soil in several ways. The removal of biomass depletes the system of nutrients such as base cations and nitrogen. After cutting the soil is exposed to sunlight and more water (due to lower evapotranspiration) and these factors can act to increase the rate of decomposition of soil organic matter. This in turn depletes the soil C pool, and decreases the number of cation exchange sites provided by organic material in the soil. There is a large literature documenting the changes in vegetation and soil following various types of biomass removal practices, such as stem-only removal, whole-tree harvesting (stems plus branches and foliage), and maximum biomass removal (above ground biomass plus stumps and coarse roots) (Ohlsson et al. 1996, Hazlett and Fleming 2009, Hazlet 2009)

We base our quantification of these effects on information given by Powers et al. (2005) as the results from the North American Long-Term Soil Productivity study. Here the changes in soil properties were measured 10 years following various types of biomass removal at 26 sites. We scale the changes proportional to the % forest cover in each lake catchment.

- Pool of soil C: After 10 years on the average 25% of the soil C pool was lost under the “all slash removed” treatment relative to the “normal harvest” treatment. The authors reason that this C is lost due to the lower input of C from litter and dead material in the extreme treatment and to the higher soil temperatures in this treatment. They believe that the effect occurs primarily during the first years after biomass removal, and would be minimal following re-establishment of the new forest. We thus assumed that with an average rotation time of 75 years that for the catchment area covered by forest 25% of the C stock in the soil would be lost. This works out to be 0.33% of the soil C stock per year on average. We further assume that all the N and BC associated with the soil C lost will be released to the soil solution at the time of decomposition thus being available for processes such as cation exchange, uptake by vegetation and nitrogen mineralisation.
- Cation exchange capacity (CEC): We assumed that 50% of the CEC was associated with organic material and 50% with inorganic minerals. Thus the change in the soil C pool causes a 50% commensurate change in the CEC. The decline in soil C stock of 0.33% per year thus gives a decrease in CEC of 0.165% per year.
- Net nutrient uptake by the forest: Maximum land use scenario assumes removal of 100% stems + 70% (branches+needles) + 100% stumps. We assume that the trees growing after the maximum biomass removal will take up sufficient nutrients from the soil to grow a new forest with the same nutrient contents as the previous generation. Since more biomass and nutrients are removed from the system, these are thus assumed compensated by comparable increase in uptake from the soil. Calculation of additional uptake from removal of stumps uses the ratios (stems+branches+needles+stumps) / (stems+branches+needles) for individual BC's and N from the Finnish study and the absolute (stems+branches+needles) for the Swedish sites (Hellsten et al. 2008).
- Runoff: assumed no change.

We assumed that forest practices shifted from current to maximum biomass removal in year 2011. Therefore these changes were implemented as a step change in the year 2011 and held constant over the entire forecast period to year 2100.

Scenario CC

Climate change, but no change in utilisation of the forest, CLE deposition scenario for S and N deposition. The exact effect of future climate change on all ecosystem processes is unknown and uncertain. In this report we modelled several of the better known CC impacts and neglected less known or less important aspects. We used one future climate scenario, the A2 scenario of the IPCC (United Nations Intergovernmental Panel on Climate Change). This is a relatively high scenario of future greenhouse gas emissions. We took the simulated future temperature, precipitation and runoff data for Sweden from the Regional Climate Model of the SMHI (Swedish Meteorological and Hydrological Institute) (Figure 5). This in turn is based on the ECHAM global climate model. Details are given on the SMHI website (www.smhi.se).

Effects of two climatic drivers - temperature and runoff - were modelled. Change in precipitation is also an important factor, but in this context only as a cause of changing runoff. Therefore the change in precipitation as such was not explicitly used in the model runs. We assumed that on annual basis future climate change will not affect the total deposition of S and N (i.e. increased precipitation will entail more water but the same amounts of ions at lower concentrations). According to calculations provided by SMHI this assumption could be made for Sweden since no clear trends in future S and N deposition could be identified due to climate change (Engardt and Foltescu, 2007). SMHI provides scenario projections on a 50x50 km resolution across Europe <http://www.smhi.se/cmp/jsp/polopoly.jsp?d=12028&l=sv>. We downloaded data covering most of Sweden. In general the outcome of A2 scenario projections with the ECHAM model did not have a strong geographical variation over a few 50x50 km squares in the same region. Therefore we divided Sweden in to three districts, northern, middle and southern. We calculated an average climate change for all 50x50 squares at each of the three districts. The average climate change was then used for counties within the geographical area of each district. Northern district comprised Norrbottens län, Västerbottens län, Jämtlands län, Västernorrlands län and Gävleborgs län. Middle district comprised Stockholms län, Uppsala län, Södermanlands län, Värmlands län, Örebro län, Västmanlands län and Dalarnas län. The southern district comprised Östergötlands län, Jönköpings län, Kronobergs län, Kalmar län, Gotlands län, Blekinge län, Skåne län, Hallands län and Västra Götalands län.

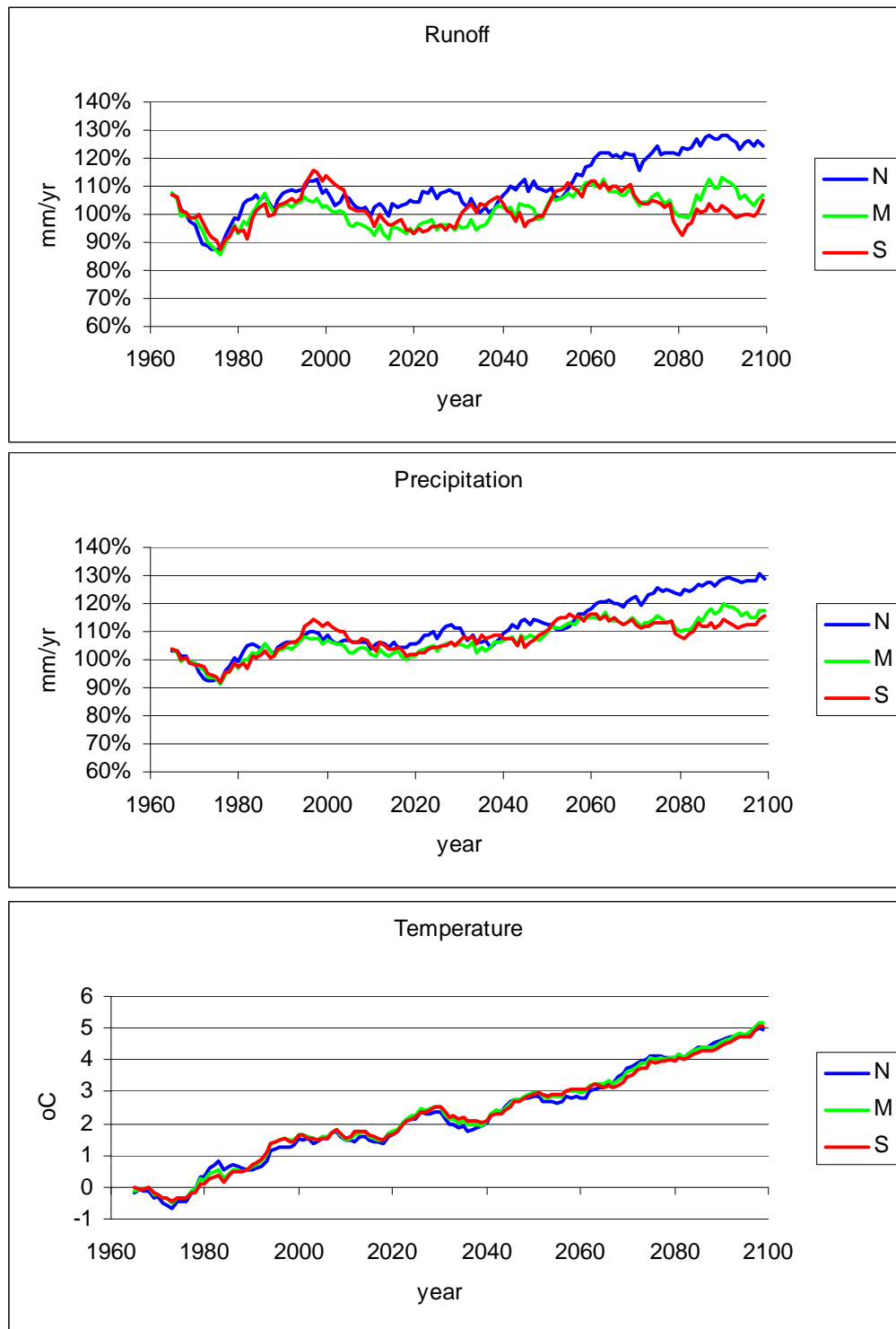


Figure 5. Projected climate change for three regions in Sweden (N=north, M=middle, S=south) according to A2 scenario using the ECHAM global climate model as downscaled to Europe by SMHI. The effect on runoff, precipitation and air temperature 2m above ground. The curves show a deviation from the reference 30 years period 1961 – 1990. The curves were smoothed by calculating 10-year moving average (data from SMHI).

To assess the magnitude of long term climate trend, the average climate 2071 – 2100 was compared to a reference period 1961 – 1990. The largest climate change is predicted to occur in northern part of Sweden (Table 1), where over 110 years the temperature is expected to rise by 4.4 °C, precipitation by 26% and runoff by 24%. The temperature rise is marginally smaller in middle

Sweden, 4.3 °C, and in southern Sweden, 4.2 °C. The expected increase in precipitation is, however, more variable across the country, ranging from the 26% in north to 15% in middle Sweden and 12% in the south. Due to higher evapotranspiration the differences in runoff are even more pronounced, ranging from the 24% in north to 6% in the middle and only 2% in the south.

Table 1. Projected changes for 100 years in the future in temperature $\Delta^{\circ}\text{C}$ and runoff (Q) for three regions of Sweden (county codes in brackets) obtained from the SMHI regional model run with the IPCC A2 scenario and the ECHAM global climate model.

	$\Delta^{\circ}\text{C}$	Q
North (X, Y, Z, AC, BD)	4.4	+24%
Middle (S, T, U, W, AB, C, D)	4.3	+6%
South (E, F, G, H, I, K, M, N, O)	4.2	+2%

County	Code
Stockholms län	AB
Västerbottens län	AC
Norrbottnens län	BD
Uppsala län	C
Södermanlands län	D
Östergötlands län	E
Jönköpings län	F
Kronobergs län	G
Kalmar län	H
Gotlands län	I
Blekinge län	K
Skåne län	M
Hallands län	N
Västra Götalands län	O
Värmlands län	S
Örebro län	T
Västmanlands län	U
Dalarnas län	W
Gävleborgs län	X
Västernorrlands län	Y
Jämtlands län	Z

These changes in temperature and runoff were assumed to affect several processes in the catchment-lake ecosystems. These were implemented in MAGIC as follows:

- Pool of soil C: A large number of experiments show that decomposition of soil organic matter increases with increased temperature (Rustad et al. 2000). We chose the results from the CLIMEX experiment in Norway to quantify this effect. Wright et al. 1998 calculated that the C pool in the soil of 760 mol/m² decreased by 1.1 mol/m²/yr due to a 3.7 °C increase in temperature. We assume that the future change in temperature will be linear starting in 2010. This corresponds to 0.02% decrease in soil C pool per year and $\Delta^{\circ}\text{C}$, where $\Delta^{\circ}\text{C}$ refers to the

projected change in temperature from the RCM between the reference period and the simulated period 100 years in the future.

- Cation exchange capacity (CEC): We assumed that 50% of the CEC was associated with organic material and 50% with inorganic minerals. Thus the change in the soil C pool causes a commensurate change in the CEC. The decline in soil C stock of 0.02% per year and °C, thus gives a decrease in CEC of 0.01% per year and Δ°C.
- Net nutrient uptake by the forest: Modelling studies indicate that the forest of Sweden will grow faster in a warmer and wetter future climate. Weslien et al. (2009) suggest that for a typical forest in northern Sweden the rotation time (time for the forest to reach maturity such that it is ready to be harvested) will decrease from 110 years to 75 years under the IPCC A2 scenario with the ECHAM GCM and the RCM run by SMHI. The Δ°C was 4.7 °C for this study. This implies that the nutrient uptake by the forest will also be faster, and that under the assumption that the mature forest has the same nutrient contents after 75 years rather than 110 years, the uptake must be increased per year. This corresponds to a 10% increase in uptake rate for BC and N per Δ°C. The change in temperature was assumed to be linear from 0 in 2010 and maximum in 2100.
- Runoff: Climate change also entails a change in precipitation, and thus runoff. The projected changes in runoff were taken directly from the SMHI website and the IPCC scenario A2 with the GCM ECHAM was used.

Scenario CCLU

Combined climate change with maximum removal of the forest biomass, CLE deposition scenario for S and N deposition. Here we assumed that the effect of climate change and increased rate of removal of biomass were simply additive, with no synergistic effects or negative feedbacks. Thus we assume that the forest growth is not limited by moisture or loss of nutrients from the system.

- Pool of soil C: the % change per year due to climate change was simply added to the % change per year due to change in forest practice.
- Cation exchange capacity (CEC): the % change per year due to climate change was simply added to the % change per year due to change in forest practice.
- Net nutrient uptake by the forest: the % change per year due to climate change was simply added to the % change per year due to change in forest practice.
- Runoff: assumed due entirely to climate change, thus set the same as for CC.

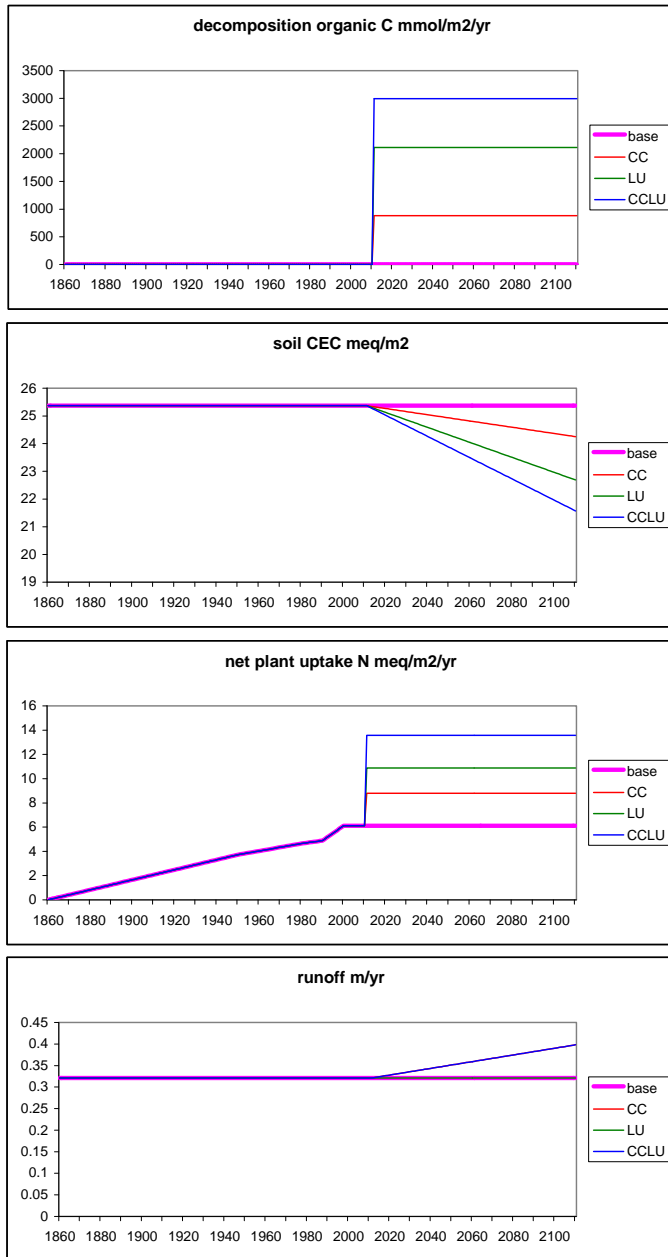


Figure 6. Changes in rate decomposition of soil organic C, soil cation exchange capacity (CEC), net uptake of N, and runoff at lake BD291 (Norrbottens län) under the historical period (1860-2010) and four future scenarios of land use and climate change.

3 Results

The initial dataset of lakes comprised 1218 lakes over all of Sweden. Of these 1151 were previously successfully calibrated using the automatic optimiser routine but with the N dynamics turned off, and 1151 accepted for the MAGIC library. This was the work done previously in response to the CCE call for data November 2008, and the results were entered into the MAGIC library

(www.ivl.se/magicbibliotek). Now using exactly the same conditions but with the N dynamics turned on, a total of 863 lakes calibrated successfully. Of these 5 did not calibrate before with N dynamics turned off. Including the N and C dynamics in the model did not change the “acidification” part of model calibration. With N dynamics nearly all of the 858 lakes had the same base cation weathering rates, the same cation selectivity coefficients, and the same initial % base cation in the soil (Figure 7) as in the calibration without the N dynamics. Only the N parameters differed.

3.1 Calibration

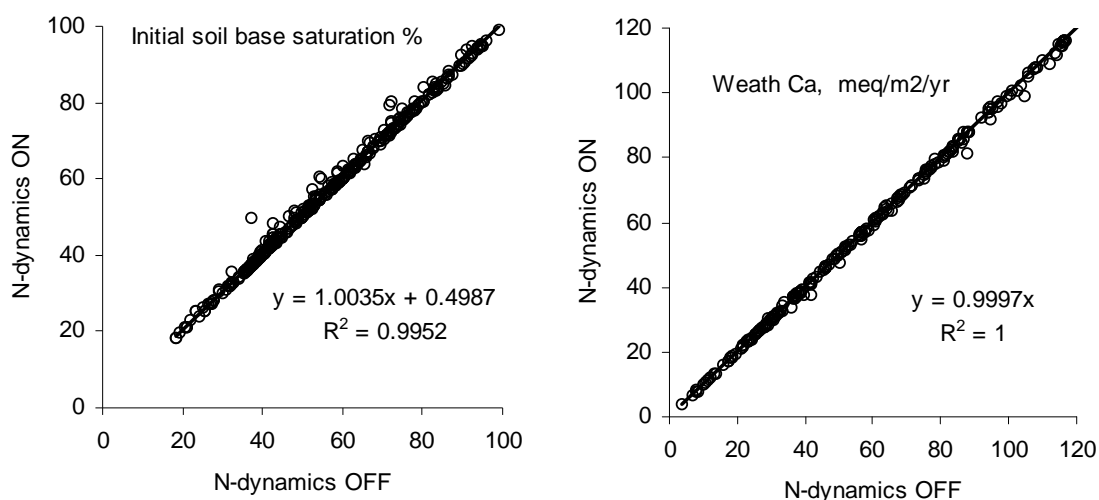


Figure 7. Comparison of initial soil base saturation and weathering rate of Ca for the 863 lakes that calibrated successfully both in the old setup with N dynamics turned off (constant % N retention over time) and the new setup here with N dynamics turned on.

The optimiser was setup to match the total inorganic N (sum of $\text{NO}_3 + \text{NH}_4$) in the lake, and indeed the simulated TIN matches the observed for the 863 lakes (Figure 8). The simulated NH_4 is equal to or lower than the observed because in setting up the calibration we assumed that no NH_4 comes from the terrestrial catchment and the sole source (often insufficient) is atmospheric deposition to the lake itself less that nitrified in the lake. This is obviously a simplification, but in the absence of observed data for the chemical composition of runoff from the terrestrial catchment, we have no objective way to determine the amount of NH_4 leached from the soil. NH_4 concentrations in the lakes were generally low in any case, and the lakes with higher NH_4 levels may be influenced by pollution from agriculture in the catchment or other source of NH_4 .

Because NH_4 is simulated equal to lower than observed, NO_3 is simulated equal or somewhat higher than observed (Figure 8). This is to satisfy the criterion that the simulated total inorganic N equals the observed.

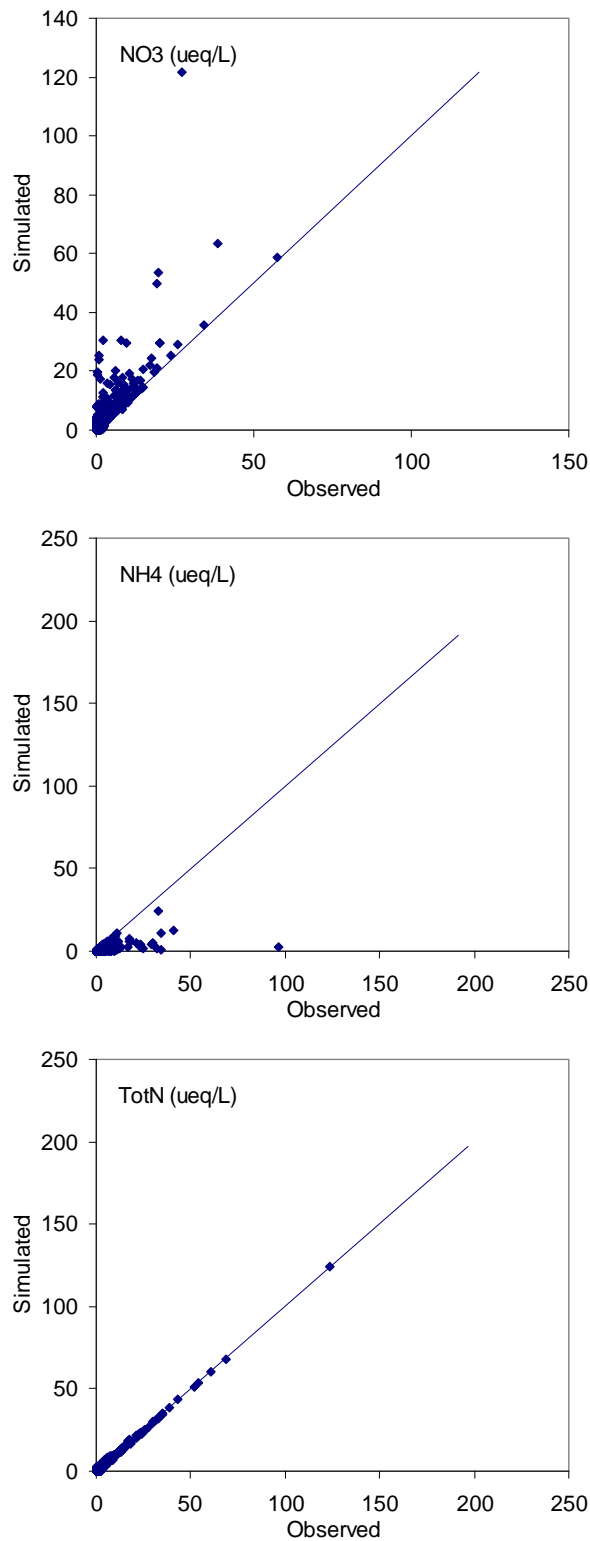


Figure 8. Simulated vs. observed concentrations ($\mu\text{eq/l}$) of NH_4 , NO_3 and total inorganic N in the 863 lakes successfully calibrated with N dynamics switched on.

The formulation of the N dynamics in MAGIC is such that it is assumed that the retention of N in the terrestrial ecosystem is governed by the “N-richness” of the system. Thus N-rich systems retain a smaller fraction of the incoming N from atmospheric deposition, as compared to N-poor systems. The measure of N-richness is taken as the C/N ratio of the soil organic matter. Soils with low C/N ratios retain less (and thus leach more) inorganic N to runoff as compared with soils with high C/N ratios. The rationale behind this view is largely based on empirical data compiled by Gundersen et al. 1998.

In MAGIC the “Gundersen” curve is formulated such that retention is 100% at C/N ratio above an upper limit (C/N_{up}) and retention is 0% below a lower limit (C/N_{lo}) (Figure 9). From the empirical data of Gundersen et al. 1998 we reasoned that C/N_{up} should be between 15 and 35 and that the difference between C/N_{up} and C/N_{lo} (width of the curve) was 10 units. Furthermore we assumed no change in the size of the soil C pool during the hindcast period. The calibration was then setup such that the simulated present-day C/N ratio in the soil matched the observed and the simulated present-day total inorganic N concentration in the lake matched the observed. The two degrees of freedom were thus the initial pool of N in the soil (initial C/N ratio) and the C/N_{up} of the Gundersen curve.

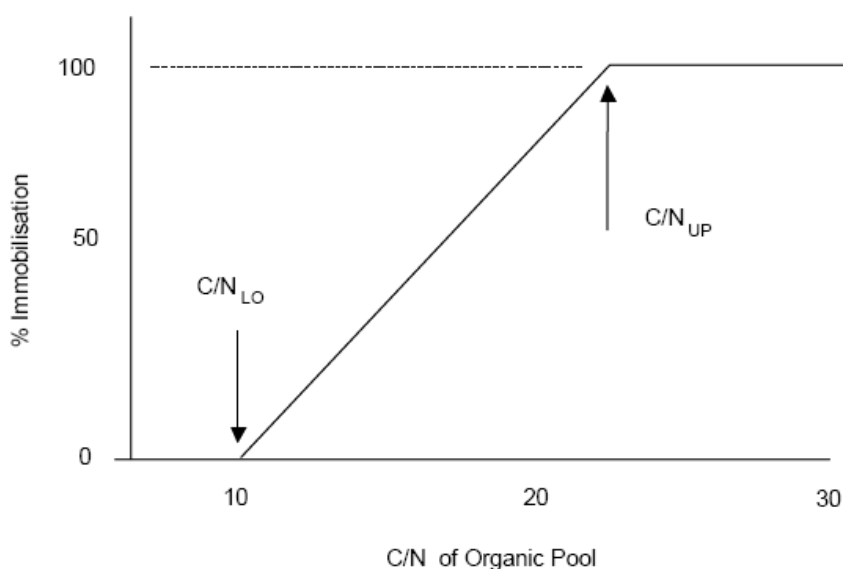


Figure 9. Schematic view of the “Gundersen curve” as used in MAGIC to regulate the retention (immobilisation) of inorganic N in soil (from Cosby et al. 2001).

The Gundersen curve has three regions. At C/N ratios (of the soil organic matter) above the upper limit the system retains 100%, and thus soils leaches no inorganic N. The observed C/N ratio is thus equal to or higher than the C/N_{up} , but there is insufficient information to know how much above C/N_{up} . Similarly at C/N ratios below the lower limit the system retains 0% and thus leaches all inorganic N. The observed C/N ratio is thus equal to or less than the C/N_{lo} , but there is insufficient information to know how much below C/N_{lo} . Only those systems that fall between C/N_{up} and C/N_{lo} have sufficient information to give a unique solution.

This is shown by the results from the optimised C/N_{up} for the 863 lake (Figure 10, upper panel). A number of lake catchments retain 100% of incoming N and thus the observed C/N is higher than the C/N_{up} (region in the figure to the right of the right-hand line); similarly a number of lake

catchments retain 0% of incoming N and thus the observed C/N is lower than the C/N_{lo} ($=C/N_{up} - 10$) (region in the figure to the left of the left-hand line). These two sets of lakes were excluded from further analysis. Finally there are a large number of lakes with soils in their catchments that optimised to $C/N_{up} = 35$ or $C/N_{up} = 15$ (the maximum and minimum allowed in the optimisation), and these were also excluded. A total of 348 lakes remained in the analysis (Figure 10, lower panel). (The abundance of lakes on the vertical line of obs C/N=26 are those with no forest that were all assigned the same soil chemistry).

In summary the calibration: 1218 lakes (and their catchments) → 1151 calibrated without N dynamics (previous work) → 863 calibrated with N dynamics → 348 lakes satisfied the C/N criteria

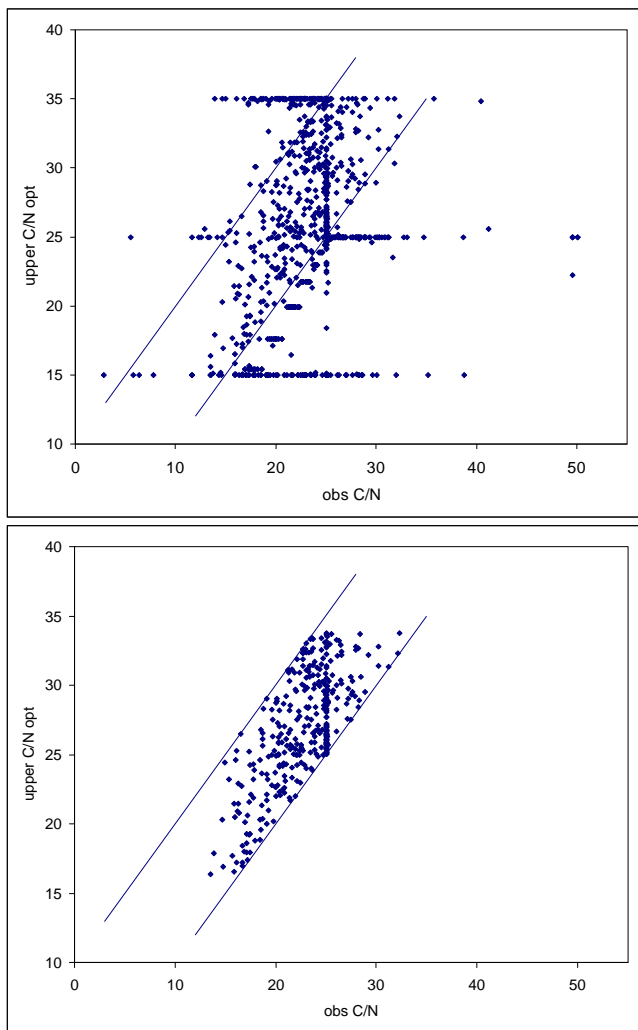


Figure 10. C/N upper limit obtained in the calibration vs. the observed present-day C/N ratio in the soil for the 863 lakes calibrated (upper panel) and the 348 lakes that satisfy the C/N criteria (lower panel).

3.2 Comparison of the present-day status for the 348 subset and 1151 library lakes

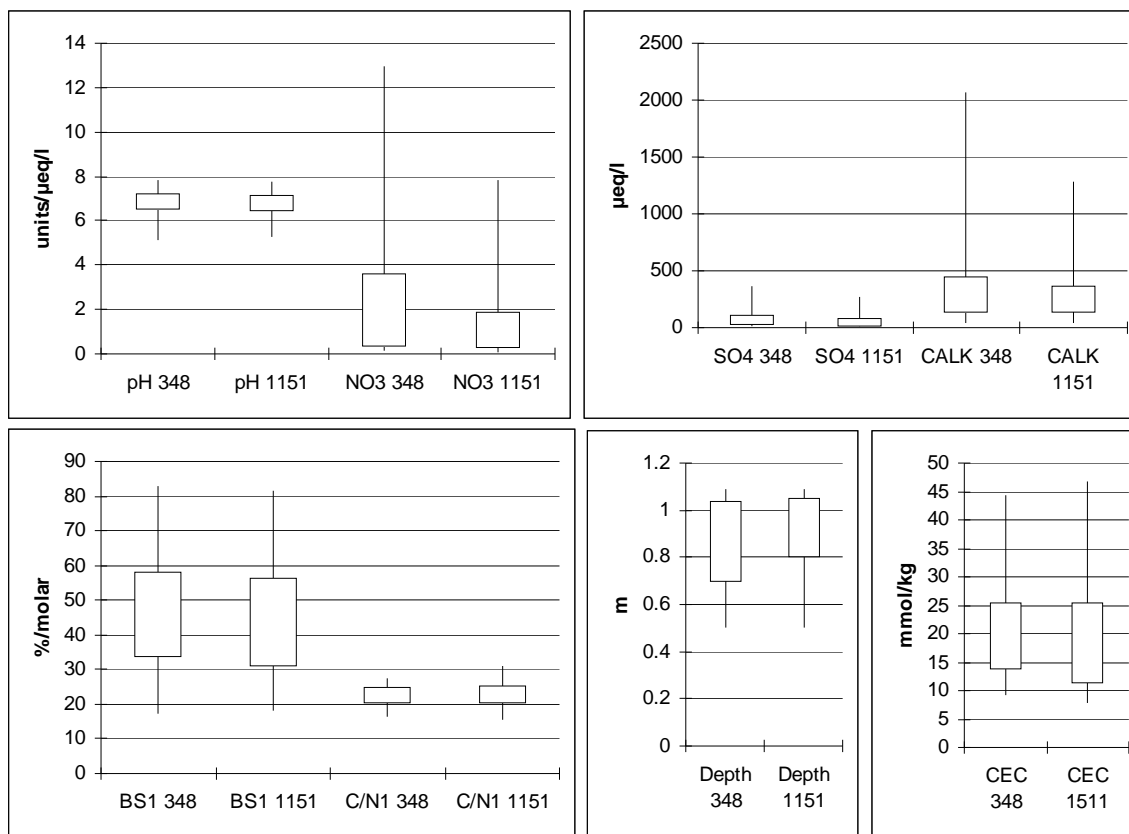


Figure 11. Comparison of present-day lake observed chemistry (2005) and soil chemical and physical parameters for 1151 lakes modelled previously with MAGIC with no N dynamics and a subset of 348 lakes re-calibrated in this study with N dynamics turned on. Boxes delimit 25 to 75%-ile of each parameter, while whiskers indicate 5 and 95%-ile. Upper row: year 2005 measured lake water: pH, NO₃ concentration, SO₄ concentration and calculated alkalinity (ANC). Lower row: soil base saturation (BS), average C/N ratio mol/mol of the soil profile, soil depth and cation exchange capacity (CEC).

The 1151 lakes modelled for the purpose of assessment tool MAGIC library (www.ivl.se/MAGICbibliotek) is a subset of lakes sampled repeatedly within national lake survey programme Riksinventeringen (www.ma.slu.se). The 348 lakes selected for this study did not differ in any major way from the bigger dataset (Figure 11). On average the 348 lakes dataset included somewhat higher proportion of lakes with elevated NO₃ concentration, which were, however, in general very low. Only 5% of the modelled lakes had NO₃ concentrations above 13 µeq/l. Also the distribution of soil parameters was comparable for both 1151 lake catchments and the 348 lake catchments subset. The soils were on average somewhat thinner and had lower CEC, but the differences were small and even smaller for soil base saturation and C/N ratio (Figure 11).

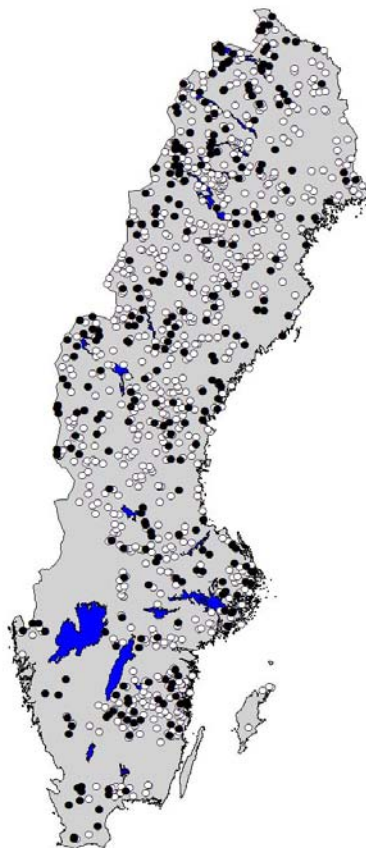


Figure 12. Location of 1151 lakes modelled with MAGIC in response to the 2008 CCE call for data and entered in the MAGIC library. Filled circles indicate the subset of 348 lakes used here to assess climate change and land use scenarios in this report.

The 1151 lakes in the MAGIC library covered the whole area of Sweden. Selection of the 348 lakes subset did not cause any apparent geographical bias to the dataset and included lakes from all parts of the country (Figure 12). Similarly, there were only minor differences in atmospheric deposition and percentage forest cover between the two full 1151 dataset and subset of 348 lakes (Figure 13). There were relatively more lakes with lower forest cover in the 348 dataset, but on average the 348 lakes had 69% forest cover while the 1151 average was 70%. The deposition of S and N was on average higher at the 348 lakes, in 2005 2.8 kgS/ha/yr at 348 lakes compared to 2.3 kgS/ha/yr at 1151 lakes. For deposition of nitrogen the average numbers were 3.7 and 3.0 kgN/ha/yr for 348 and 1151 lakes, respectively.

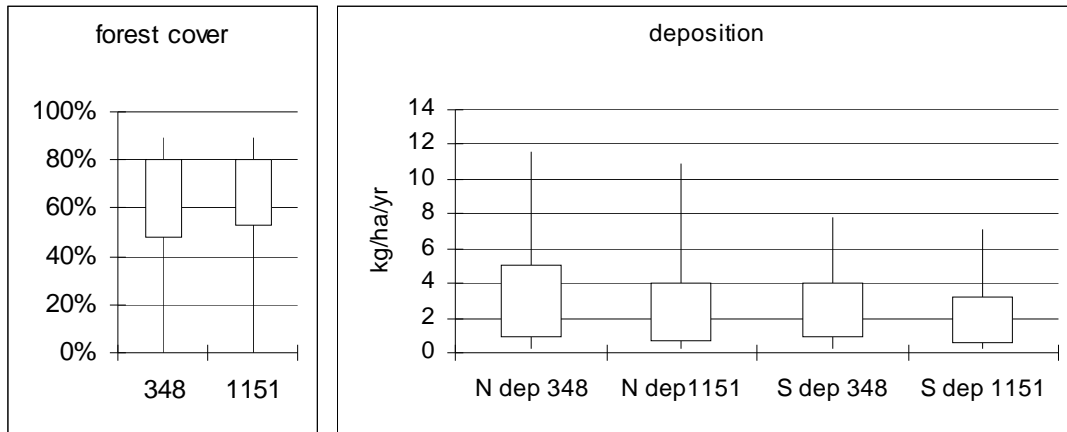


Figure 13. Comparison of % forest cover in the lake catchments and atmospheric deposition of sulphur and nitrogen in the year 2005.

3.3 Time tracks for example lakes

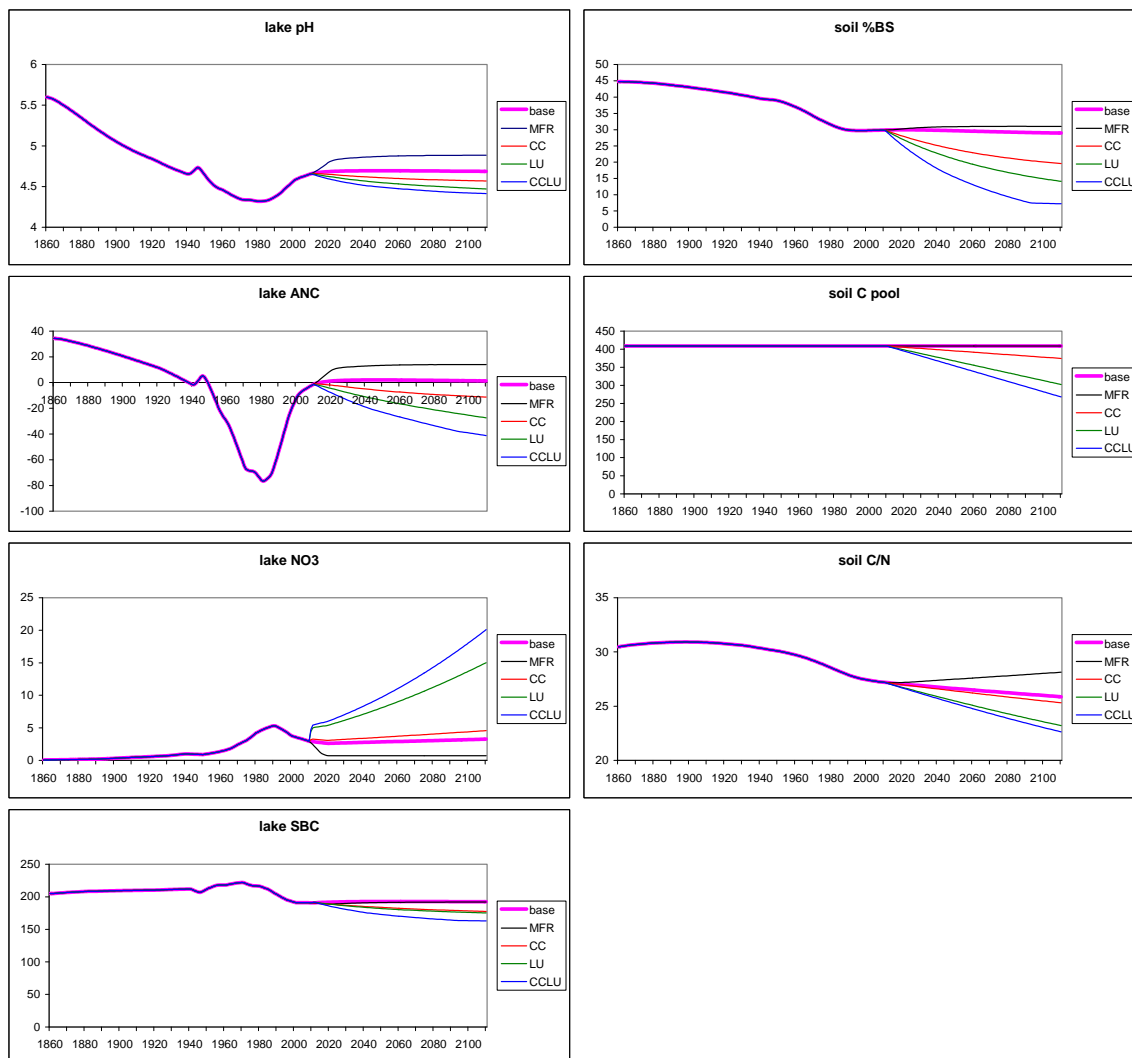


Figure 14. Example lake in southern Sweden (O077 Västra Götalands län). Simulated lake and soil chemistry for the historical period and with the 2 S+N deposition scenarios under the base case and the three biomass removal and climate scenarios in the future. Units for lake chemistry: $\mu\text{eq/l}$. ANC = acid neutralising capacity, SBC = sum of base cations, %BS = soil base saturation

The general trends over time and the differences between the various scenarios are well-illustrated by the results from two example lakes, one in southern Sweden and one in northern Sweden. Lake O077 Västra Götalands län (Figure 14) is a typical acid-sensitive and acidified forest lake. The MAGIC reconstructed pH trace suggests that this lake originally had pH about 5.5 and ANC 40 $\mu\text{eq/l}$ but was acidified during the 1900's to pH 4.5 in the mid-1980's. MAGIC indicates that concentrations of NO_3 increased as the soil pool of N increased (low C/N in soil), and soil % base saturation decreased. During the past 25 years (1985-2010) this lake has partially recovered from acidification, in response to the large decrease in S deposition. Depending on scenario for the future, recovery will continue, stop or be reversed. In the base-line scenario not much will happen, but scenarios for both climate change and increased biomass removal will cause re-acidification,

with the most extreme case being the combined CCLU scenario (Figure 14). Only if there are further reductions in S deposition will recovery continue into the future (the MFR scenario).

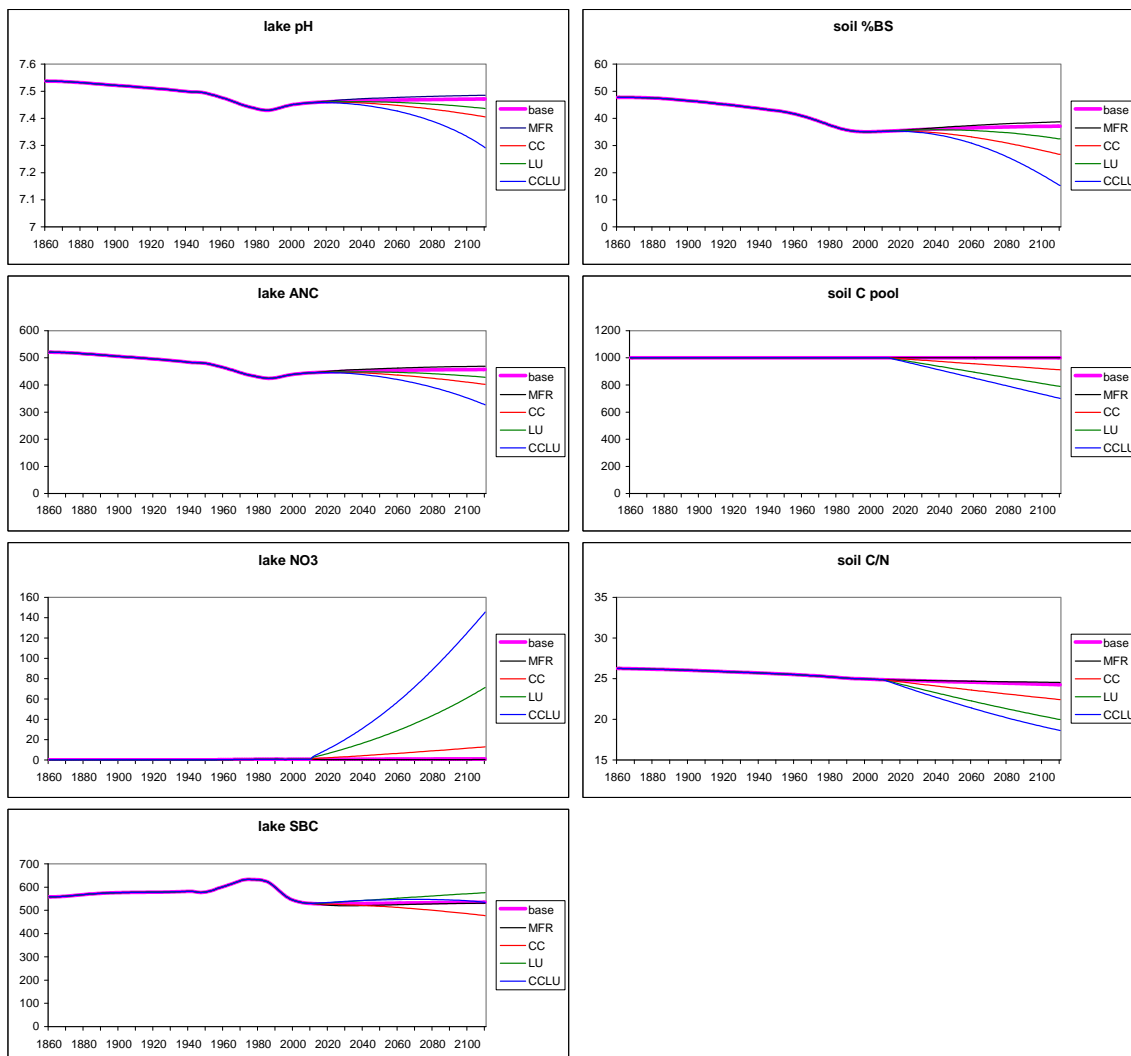


Figure 15. Example lake in northern Sweden (BD 291 Norrbottens län). Simulated lake and soil chemistry for the historical period and with the 2 S+N deposition scenarios under the base case and the three biomass removal and climate scenarios in the future. Units for lake chemistry: $\mu\text{eq/l}$. ANC = acid neutralising capacity, SBC=sum of base cations, %BS=soil base saturation

The other example lake is in northern Sweden (BD 291 Norrbottens län) (Figure 15). It is not-acid sensitive as it is well buffered and has high ANC and high pH, located in the northern part of the country where both historical and present S and N deposition has been relatively low. Thus the historical time traces (as reconstructed by MAGIC) suggest very little change in the past. In the future, however, there could be major increases in NO_3 concentrations, depending on the future scenario. Highest leaching of N is projected to occur under the LU and combined CCLU scenarios.

3.4 Future changes in lake chemistry

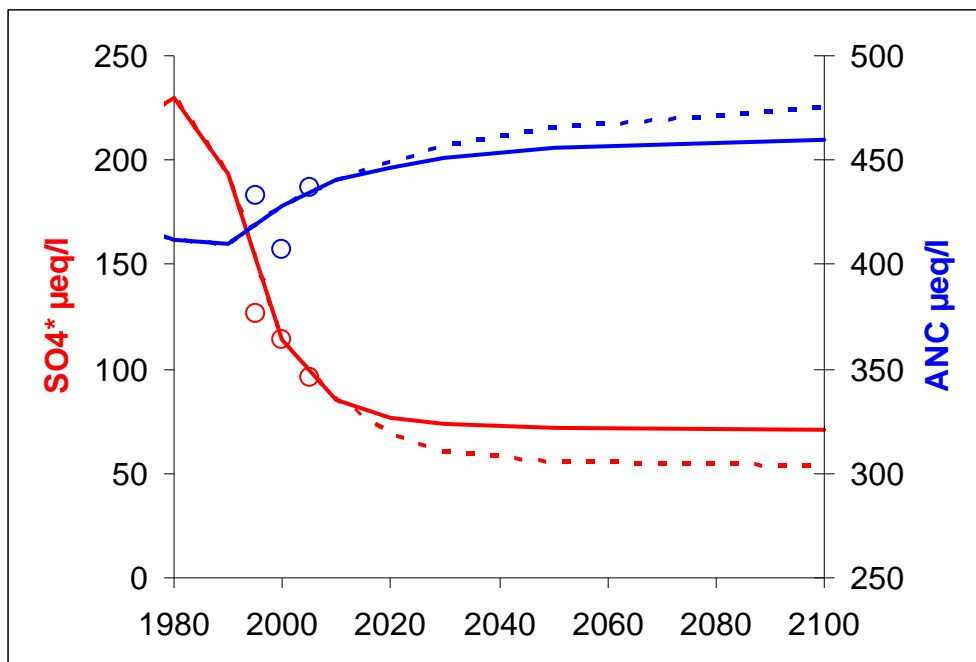


Figure 16. Average lake water SO_4^* (sea salt corrected, red colour, left Y axis) and ANC (blue colour, right Y axis) for the 348 lakes under base case with CLE deposition (solid lines) and MFR deposition (dashed lines) scenarios. Circles are average lake water SO_4 and ANC in 1995, 2000 and 2005. Note the 250 $\mu\text{eq/l}$ offset on right Y axis.

Table 2. Average lake water chemistry for the 348 lakes under the all modelled scenarios. SO_4^* denotes the non-marine fraction of sulphate.

	1860	1980	2010	2100				
$\mu\text{eq/l}$	all scenarios			base	MFR	CC	LU	CCLU
SO_4^*	40	230	114	71	54	66	71	66
ANC	518	412	441	460	475	430	435	377

By year 2010 almost all the expected recovery from acidification due to air pollution controls will have occurred (Figures 14 and 15, Table 2). In 1990 the average ANC was 410 $\mu\text{eq/l}$, i.e. 108 $\mu\text{eq/l}$ below the modelled 1860 pre-industrial value of 518. By the year 2010, twenty years after 1990, the average ANC increased by 31 $\mu\text{eq/l}$ to 441 $\mu\text{eq/l}$. Further average increase of 19 $\mu\text{eq/l}$ over the next 90 years was simulated under the base scenario (CLE deposition), and even more, 34 $\mu\text{eq/l}$, under the MFR scenario (Figure 16). ANC is thus expected to end up at best 43 $\mu\text{eq/l}$ and at worst 58 $\mu\text{eq/l}$ below pre-industrial level (Table 2).

Under all the other future scenarios, however, the results suggest that recovery from acidification will stop and majority of the lakes will decline in ANC over the next 90 years (Figure 17). Much of this decline is apparently due to increased flux of N from catchment soils to surface waters.

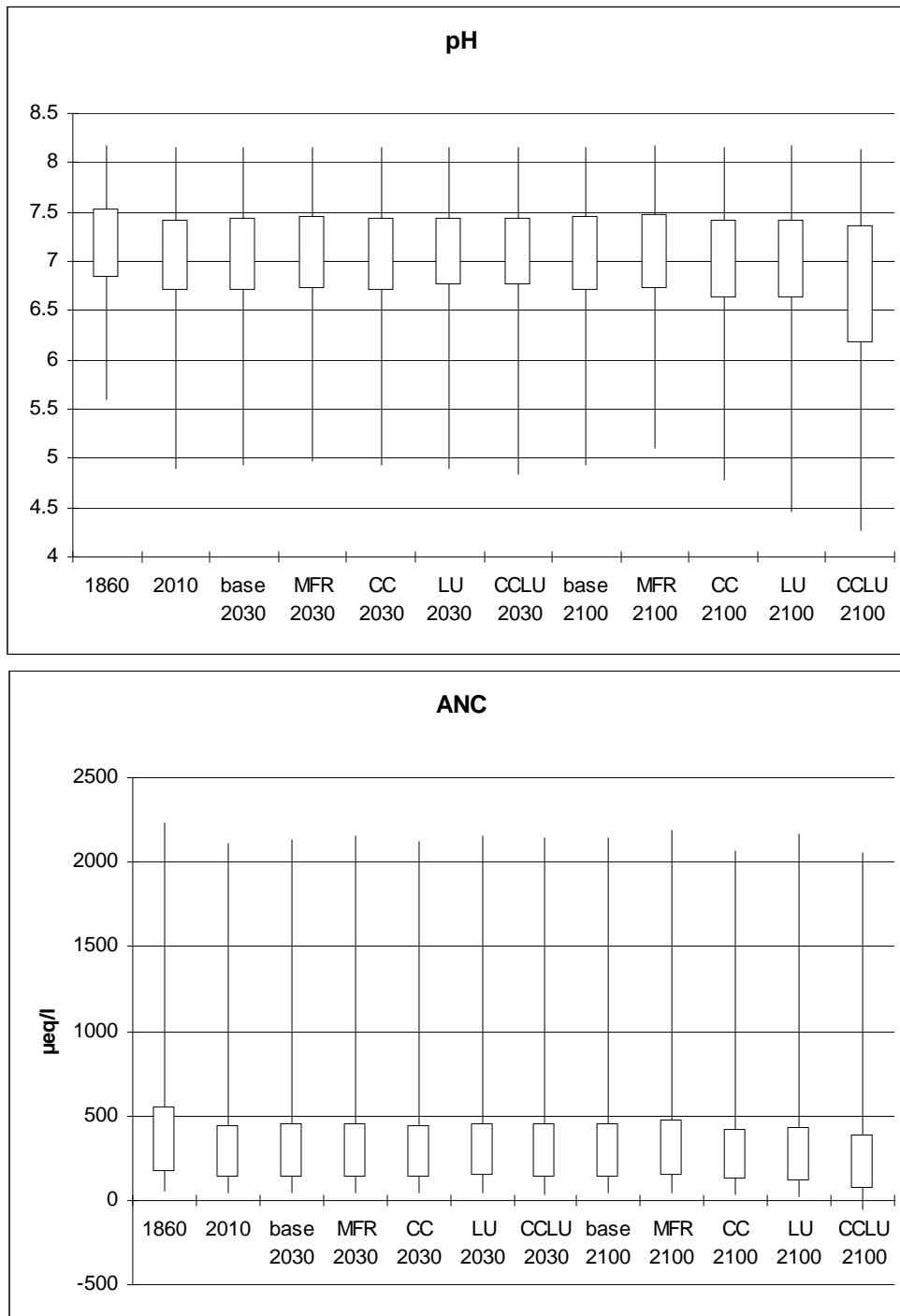


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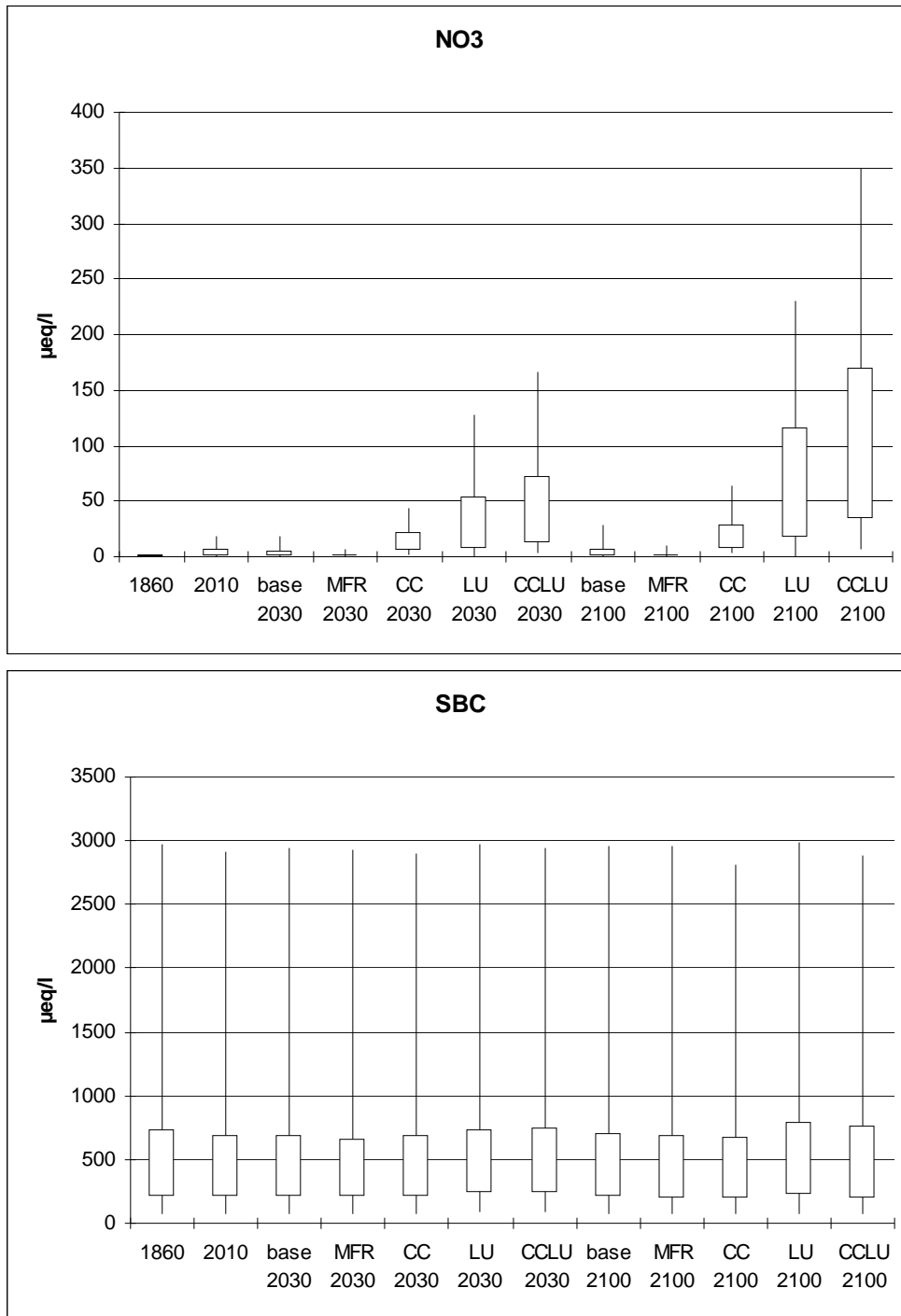


Figure 17. Lake water chemistry in 1860 and 2010 (for all scenarios) and future predictions (years 2030 and 2100 shown) for base, MFR, CC, LU and CCLU scenarios. Boxes enclose 50% and high-low lines 90% of the values for the 348 modelled lakes.

The modelled lakes represent many different types of lakes distributed over the whole 450 000 km² area of Sweden. Therefore the variability of lake water chemistry is also considerable. In the perspective of this large variability, the changes in lake water chemistry as a whole were modest under all the future scenarios with the exception of marked increases of NO₃ concentrations for the CC, LU and CCLU scenarios (Figure 17, Figure 18, Figure 19). The mean differences between years 2010 and 2100, however, were considerable. The CCLU scenario resulted in large decrease in ANC in lake water driven largely by the increase of NO₃ at practically all lakes (Figure 20, Figure 21, Figure 22 and Table 3). In this respect the results of the combined scenario CCLU was greater than the simple sum of the CC and LU scenarios due to non-linearity of the key modelled ecosystem processes.

Table 3. Lake water pH and ANC, concentrations of NO₃ and of the sum of base cations (SBC) in year 2010, and mean change from year 2010 to year 2100 for the four future scenarios. SO₄* denotes the non-marine fraction of sulphate. Change calculated as median of 348 individual differences from 2010 to 2100.

	median change 2100-2010					
	median 2010	base	MFR	CC	LU	CCLU
pH	7.1	0.0	0.0	0.0	0.0	-0.1
ANC $\mu\text{eq/l}$	247	2	9	-11	1	-39
SO ₄ * $\mu\text{eq/l}$	38	-10	-22	-15	-10	-15
NO ₃ $\mu\text{eq/l}$	1	0	-1	11	50	86
SBC $\mu\text{eq/l}$	355	-7	-6	-16	25	-2

Table 3 provides a comparison of modelled median changes. The response of individual lakes was, however, variable in magnitude and even in direction of change. That is to be expected given the variability of modelled lakes, variability of soils and past and present acidification and land use in lake catchments, and climatic and deposition gradients across the country.

The extent of variation among the lakes concerning projected future change in ANC and pH is illustrated in Figures 18 and 19. In these figures the lakes were ordered along the x-axis by the amount of change. Almost all the lakes were projected to increase in ANC and pH under the base and MFR scenarios (Figure 18, top two rows of panels). For majority of the lakes these increases were small. There were several of tens of lakes, however, where the increase was 50 $\mu\text{eq/l}$ or more. Under the CC and LU scenarios, on the other hand, a significant number of lakes show decreasing ANC and pH (Figure 18, bottom three rows of panels). The mean change of ANC under the LU scenario was modest 1 $\mu\text{eq/l}$ (Table 3). Figure 18, however, shows that there were lakes with both increasing and decreasing ANC, that changes were substantial for many lakes and that in extreme cases ANC either increased or decreased by >200 $\mu\text{eq/l}$.

Similarly the future projected changes in NO₃ and SBC concentrations differ between the various scenarios. Under the base and MFR scenarios most lakes show no change in NO₃ (Figure 19 top left two panels), whereas under the CC and LU scenarios and especially the CCLU scenario a large fraction of the lakes are projected to have increased NO₃ in the future (bottom left three panels). For SBC the results indicate that although the mean change for all the lakes is nearly zero, under all the scenarios there will be a significant number of lakes with decreasing SBC and a second set with increasing SBC (Figure 19, right-hand panels).

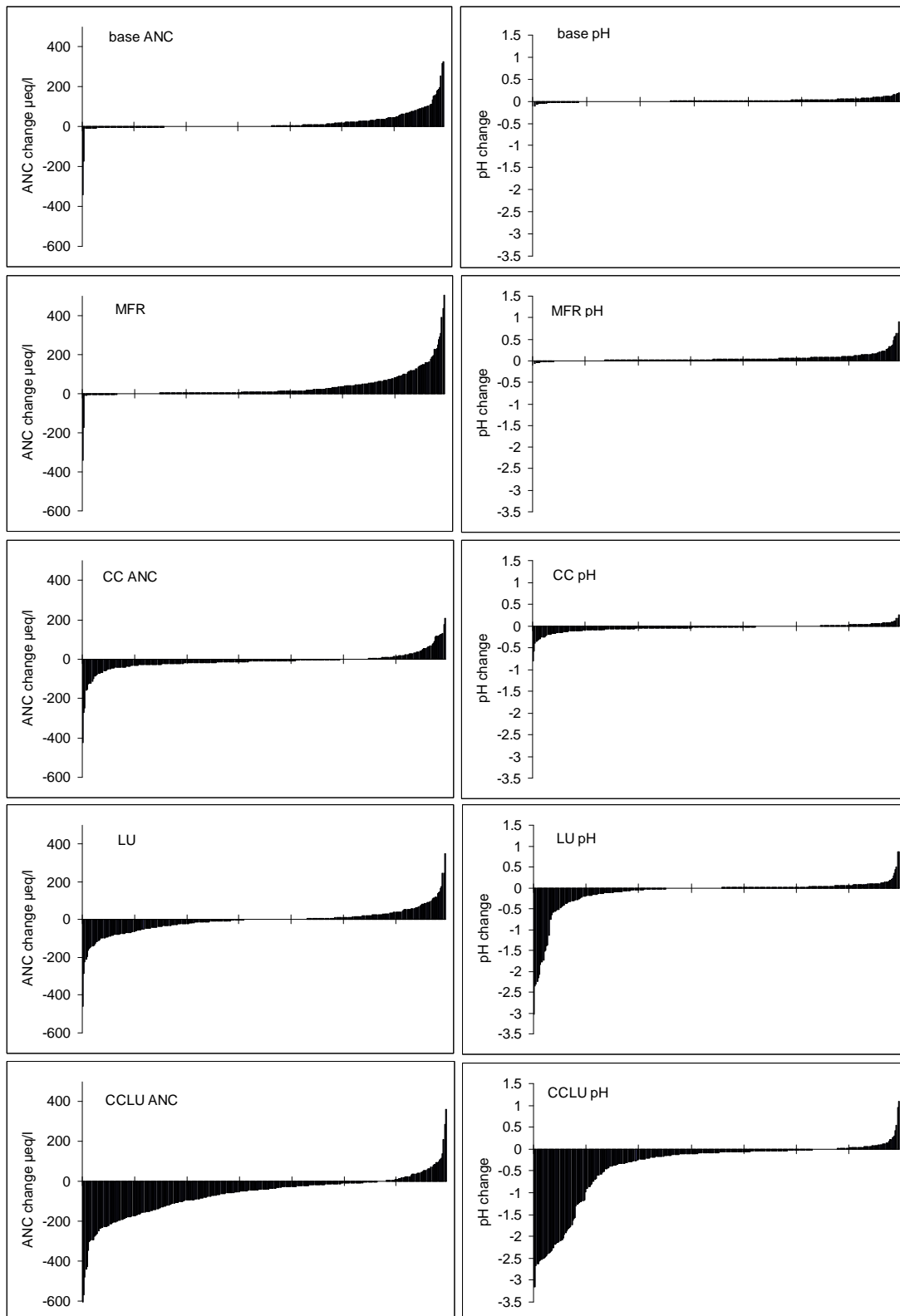


Figure 18. Change in lake water ANC (left panels) and pH (right panels) from 2010 to 2100 under 5 modelled scenarios. Each of 348 lakes represented by one vertical lines, tick marks every 50 lakes.

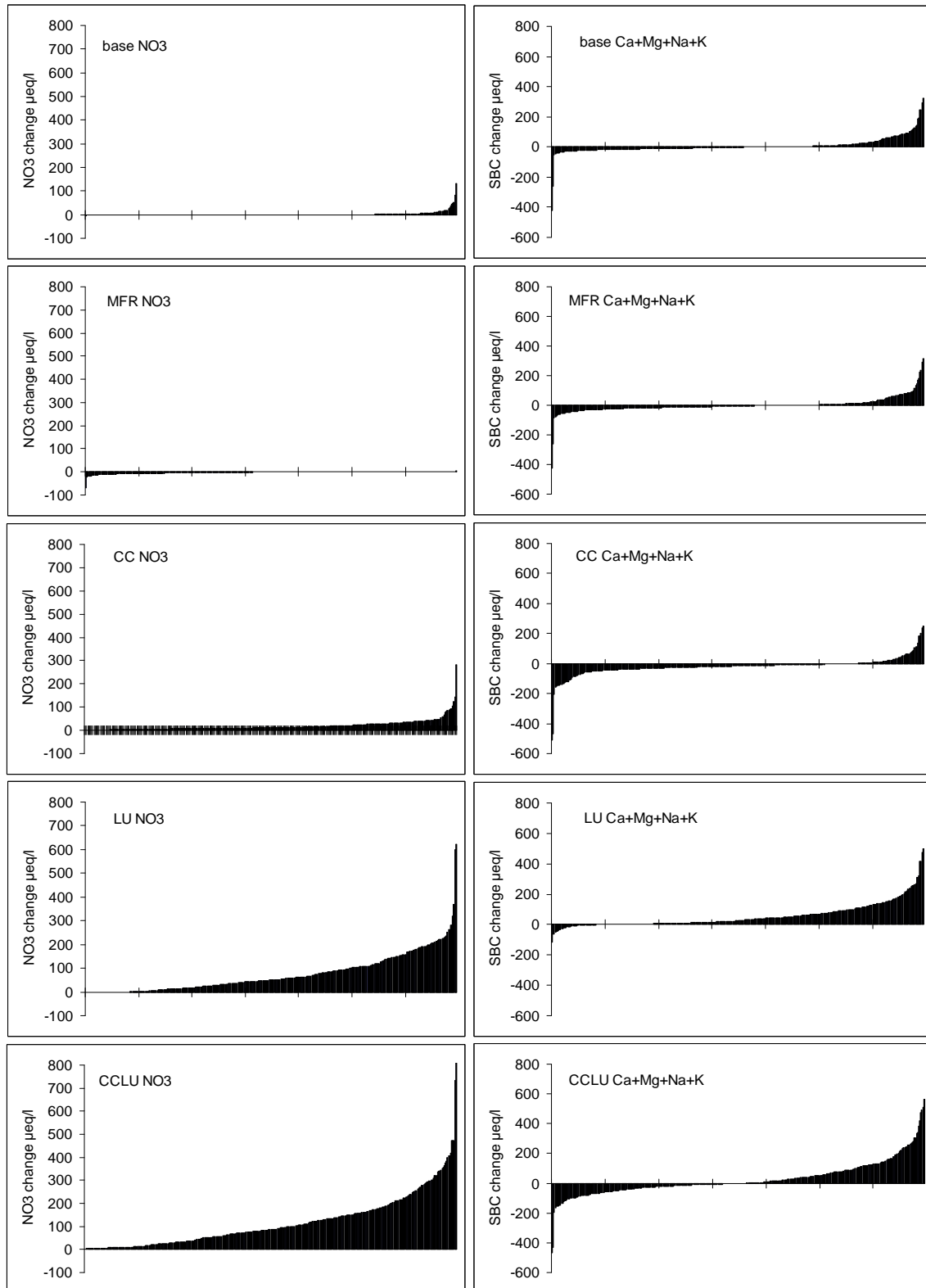


Figure 19. Change in lake water NO₃ (left panels) and sum of base cations (right panels) from 2010 to 2100 under 5 modelled scenarios. Each of 348 lakes represented by one vertical lines, tick marks every 50 lakes.

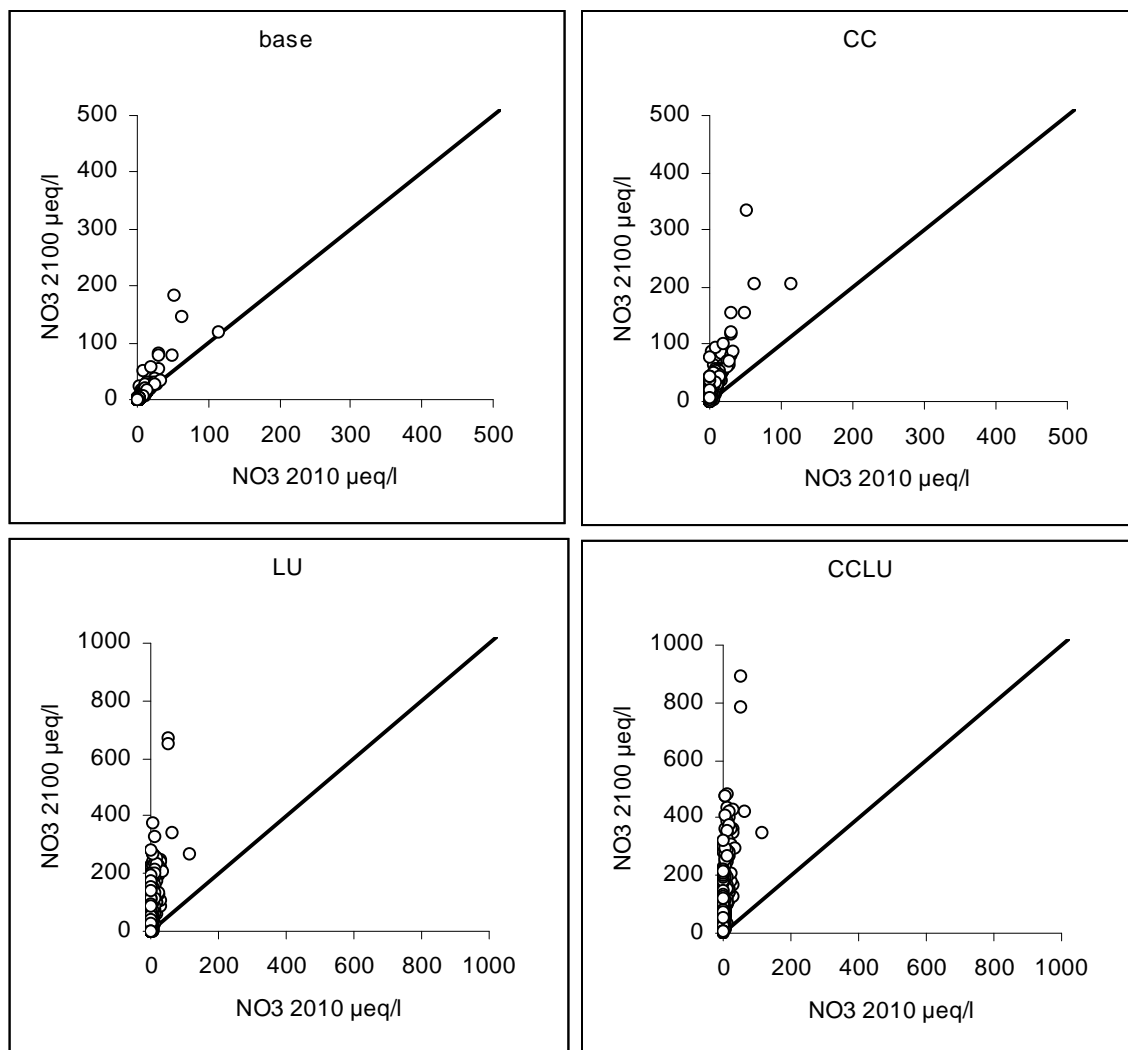


Figure 20. Scatter plot of simulated lake water nitrate concentrations in 2010 (x axis) and in 2100 (y axis) according to the four modelled scenarios. Each dot indicates one modelled lake. The diagonal is the 1:1 line. All lakes above the 1:1 line experienced increased NO_3 concentrations. Note the two-fold difference between scales in the upper two panels (base and CC scenarios) and lower two panels (LU and CCLU scenarios).

The projected future changes can also be visualised by means of scatter plots showing present-day concentrations on the x-axis and projected future concentration for the year 2100 on the y-axis. This is shown for NO_3 concentrations for four future scenarios (Figure 20), and here it is clear that in all cases NO_3 concentrations are projected to increase, and that the increases will be largest for the LU and CCLU scenarios.

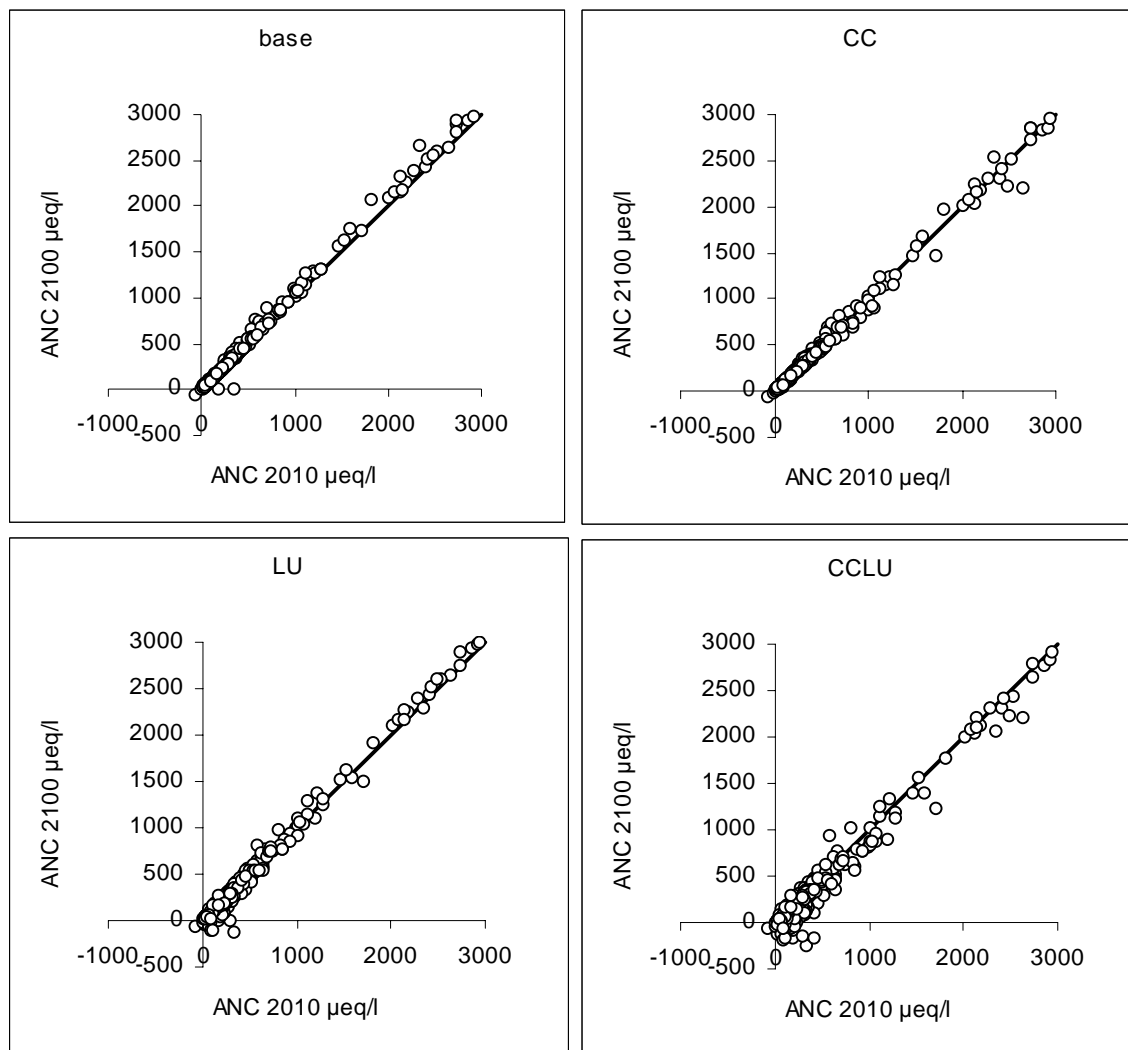


Figure 21. Scatter plot of simulated lake water ANC in 2010 (x axis) and in 2100 (y axis) according to the four modelled scenarios. Each dot indicates one modelled lake. Diagonal is the 1:1 line. Lakes above the 1:1 line were predicted to experience an increase and the lakes below the line decrease in ANC during the period 2010-2100.

The scatter plots for ANC, on the other hand, show projected future changes in both the positive and negative directions (Figure 21). In contrast to NO_3 , however, the relative changes in ANC are projected to be rather small. In general the lakes with low ANC (acid-sensitive lakes) are projected to acidify (decrease in ANC) in the future under the LU and CCLU scenarios.

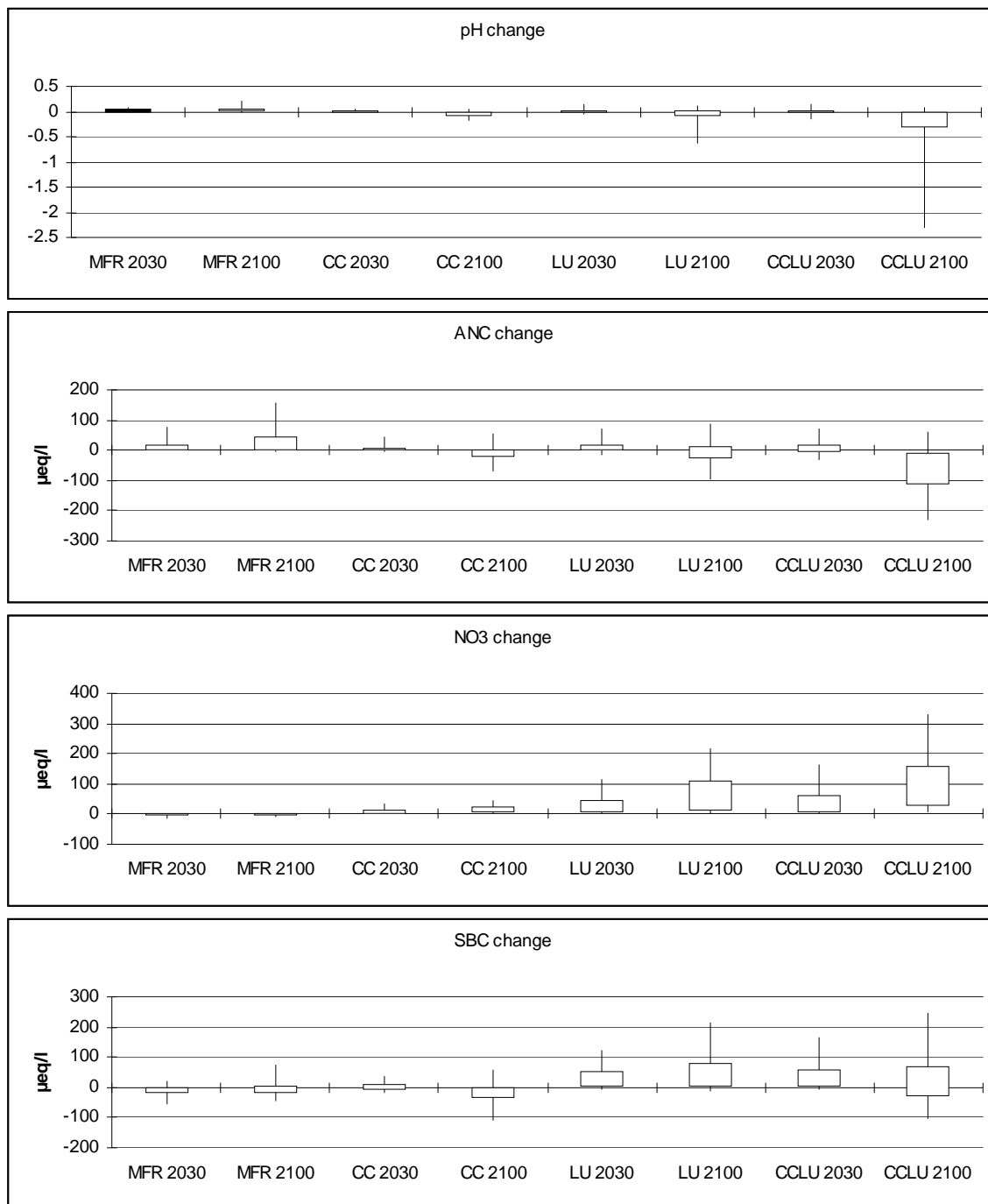


Figure 22. Mean change in lake water chemistry from 2010 to 2030 and to 2100 for MFR, CC, LU and CCLU scenarios. Boxes enclose 50% and high-low lines 90% of 348 modelled lakes.

A third way of displaying the results is by bar-and-whisker plots. These show the median and percentile values for the 348 lakes. In Figure 22 the changes in concentrations in years 2030 and 2010 relative to year 2010 are shown for pH, ANC, NO₃ and SBC. For pH the results indicate that for most of the lakes only small changes are expected in the future except under the combined

CCLU scenario. ANC is projected to increase under the MFR scenario, but decrease under the CC, LU and CCLU scenarios. NO₃ is projected to increase as is SBC.

These various presentation methods focus on different aspects of the results. The absolute values are shown in Figure 17, the extremes are best illustrated by the rank-plots in Figures 18-19, the relative changes shown in Figures 20 and 21, and the mean changes shown in Figure 22. All these show in general that with MFR there will be a small amount of recovery in the future. Further under the CC and LU scenarios (and especially the CCLU scenario) there will be increased NO₃ leaching from the soils which will offset to a lesser or greater degree the recovery from acidification. In acid-sensitive lakes re-acidification can be expected, whereas in well-buffered lakes very little change in lake chemistry (except for NO₃) is projected to occur.

3.5 Future changes in soil chemistry

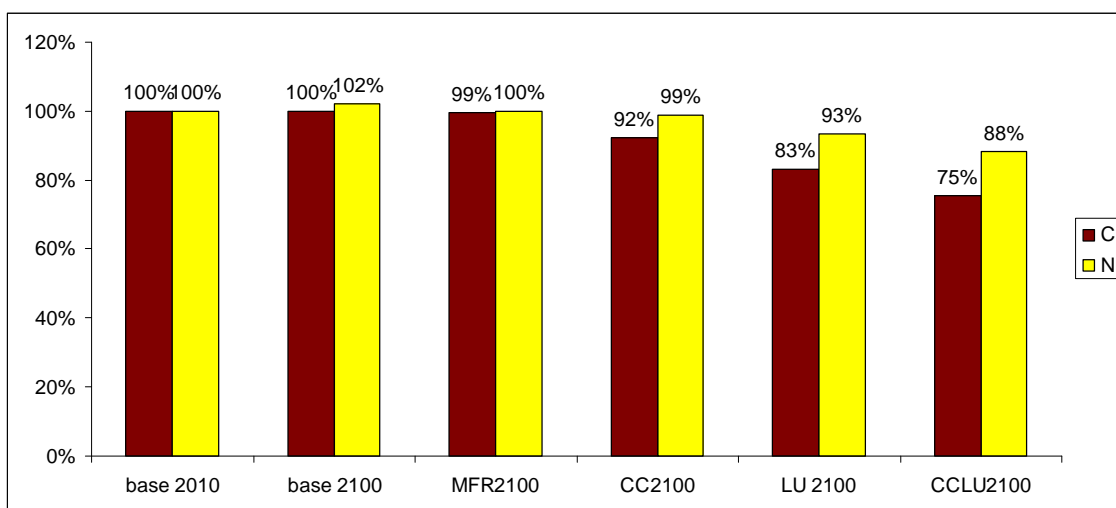


Figure 23. Average change of C and N soil pools in the catchments of the 348 lakes from year 2010 to year 2100 for the four scenarios expressed relative to soil pools in 2010.

The scenarios LU and CC both will have an impact on soil pools of C and N. Soil organic carbon was in the model assumed lost as CO₂ to the atmosphere due to increased decomposition of soil organic matter. Nitrogen was lost from soil in two ways; via leaching of nitrate to runoff and via uptake to the trees and subsequent harvest. On average, over the next 90 years LU alone will cause a 17 % loss of soil organic C, while climate change alone will cause loss of 8%. The combination of maximum biomass harvest and climate change (CCLU) will lead to a 25% loss of soil organic C. Similarly for N, the LU alone will cause loss of 7% and CC alone 1%, while the CCLU scenario will cause the largest loss of 12%. Under all the scenarios the soil organic matter will become more N rich. The soil C/N ratio will decrease on average by 0.4 and 0.1 under base and MFR scenarios and by 1.5, 2.4 and 3.2 in the CC, LU and combined CCLU scenarios, respectively (Figure 23 and Table 4)

Table 4. Average absolute sizes of soil pools of C, N and base cations (BC) and average soil organic matter C/N ratio for the 348 lake catchments.

	base 2010	base 2100	MFR2100	CC2100	LU 2100	CCLU2100
C mol/m ²	833	833	828	768	692	627
N mol/m ²	37.4	38.2	37.3	37.0	34.9	32.9
C/N mol/mol	22.5	22.1	22.4	21.0	20.1	19.3
BC eq/m ²	8.6	8.7	8.6	7.7	7.5	6.1

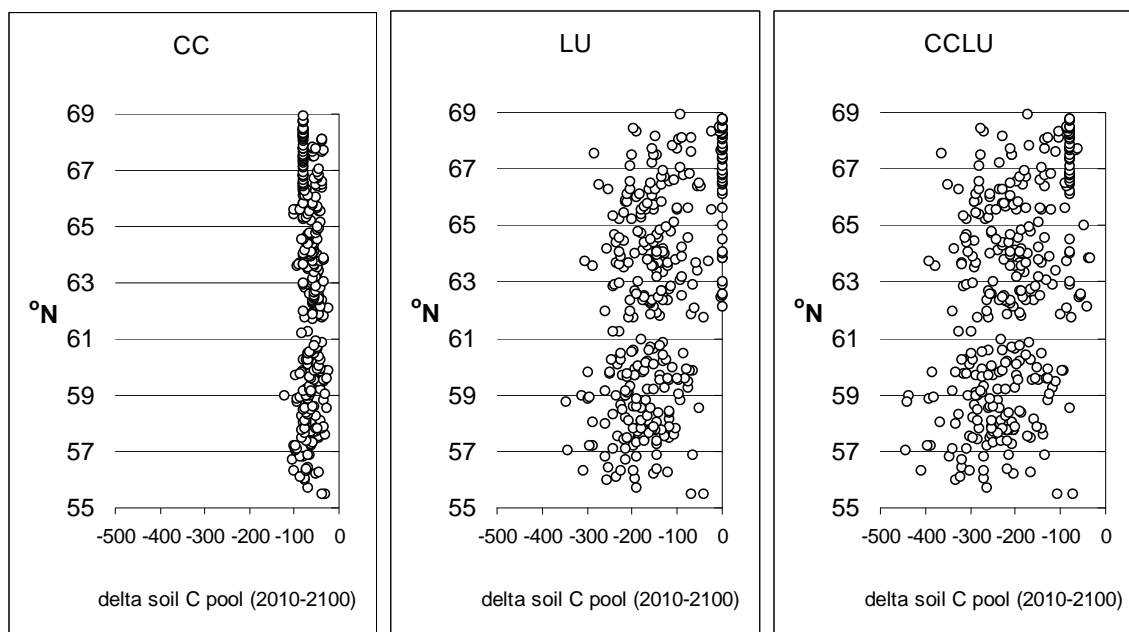


Figure 24. Simulated change in soil C pool under three scenarios from year 2010 to year 2100 plotted against degrees northern latitude. Units: molC/m².

There was very little south-north gradient in loss of soil C predicted under the CC scenario (Figure 24). This was expected since the predicted temperature increase was only marginally different in the south (4.2 °C) and north (4.4 °C). Maximum land use (LU) and consequently combination of land use and climate change (CCLU) did show a slight tendency to a higher C loss in south compared to north (Figure 24). There was also a group of lakes in the dataset which did not have any forestry in their catchments. At these lakes no increase in harvesting biomass was modelled and the change in soil pool due to the land use was zero. These are also lakes where no forest soils were sampled. In the absence of soils data an average soil profile typical for mountain areas was assumed. The C pool was therefore modelled the same at all these lakes. Since the temperature change was nearly the same across the country, C loss in CC scenario was also the same for these soils. These are the lakes with modelled C loss of 72 mol/m², forming a vertical “line” in the data in the LU and CCLU panels in Figure 24.

On average the soil pool of exchangeable base cations (BC) was little changed after 90 years in the base scenario (Table 4, Figure 25). In fact the average pool size actually increased by about 1% and 4% in the base and MFR scenarios. That means that on average the sum of losses of BC due to present-day tree harvest practices (stems plus 30% of branches and foliage) and leaching of BC to runoff due to the S and N deposition remaining under the CLE scenario are largely in balance with

the sum of BC supply from mineral weathering and deposition of base cations. Under the CC, LU and CCLU scenarios, however, soils were on average depleted of exchangeable BC by 11%, 13% and 29% respectively (Table 4, Figure 25). The results suggest that depletion of base cations in the soil will be most severe under the CCLU scenario (Figure 25). This future projected loss of soil base cations under the CC, LU and CCLU scenarios did not show a strong south-north gradient in loss of soil BC (Figure 26). This is because the depletion of base cations under these scenarios is driven primarily by increased biomass removal (LU scenario) and more rapid forest growth (CC scenario) and both these factors will occur over the entire country. The south-north gradient in S and N deposition apparently plays a lesser role in the future under these scenarios.

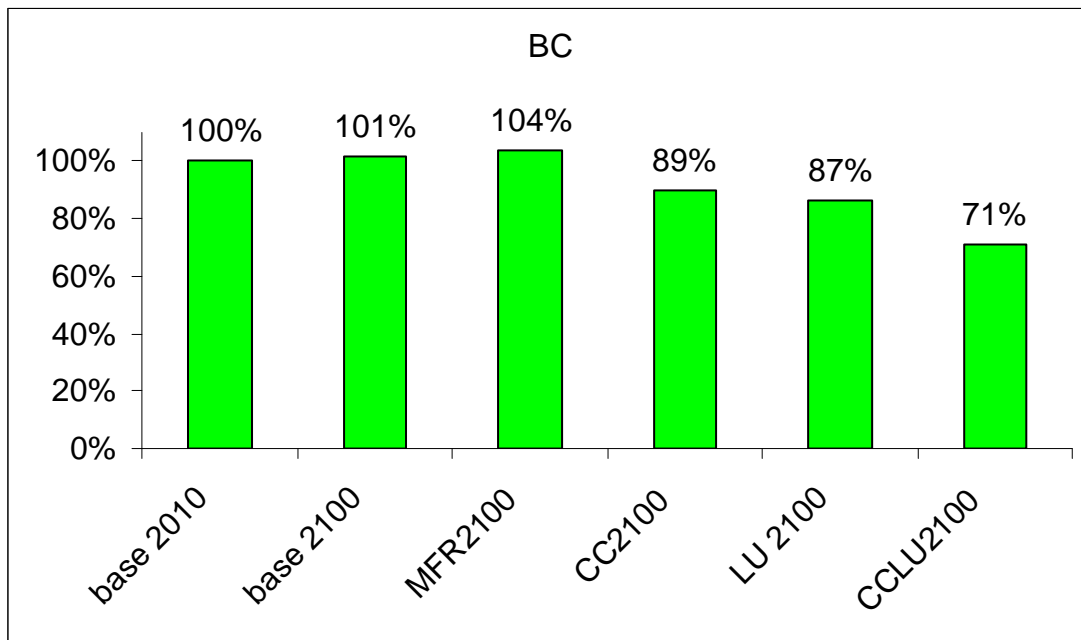


Figure 25. Average pools of exchangeable base cations (Ca^{2+} , Mg^{2+} , Na^{+} and K^{+}) in catchment soils in year 2010 and under the four future scenarios in year 2100.

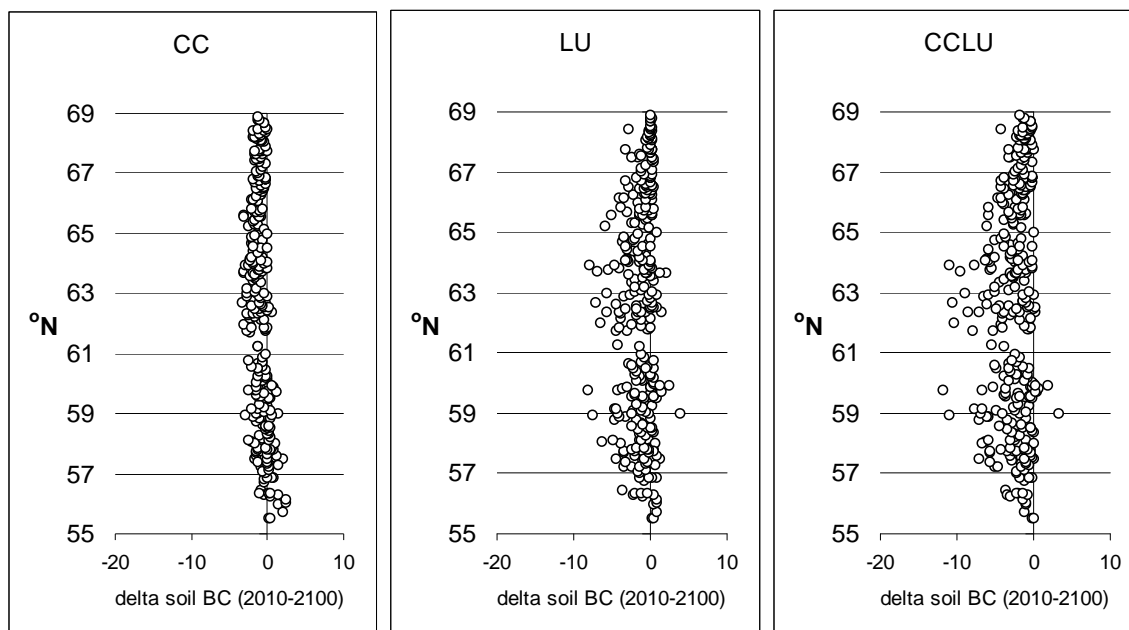


Figure 26. Simulated change in pool of exchangeable base cations in catchment soils under the three scenarios from year 2010 to year 2100 plotted against degrees northern latitude. Units: eq/m².

4 Discussion

1218 lakes vs 348 lakes

The results show that the 348 lakes used here for this scenario analysis are a representative subset of the original 1218 statistically-selected lakes in Sweden. Thus the results for the scenario runs on the 348 lakes can be taken as approximately representative for the whole population of Swedish lakes, although this has not been tested statistically.

CLE vs MFR

By the year 2010 almost all the chemical recovery expected under the CLE emission scenario for S and N will have occurred, and no further improvement in lake water chemistry can be expected unless new reductions in S and N emissions are forthcoming in Europe. The results for the MFR scenario clearly show that there is room for further improvement of lake chemistry if reductions are reduced beyond 2010 levels.

This is the case for several acid-sensitive lake districts in Europe. In addition to southern Sweden, also southern Norway, parts of the UK and the Czech Republic can gain from further reductions in S+N emissions relative to CLE (Wright et al. 2005).

The MFR scenario is for maximum reduction of S and N emissions using currently-available technology. This is not a fixed parameter, however, because technological improvements are continually being made. Furthermore future S and N emissions may decrease due to “co-benefits” of controls on greenhouse gases. This is especially the case for CO₂, where a lower use of fossil fuels may be one of the major steps taken to reduce emissions. Reduced use of fossil fuels may thus give co-benefits in terms of reduced emissions of S and N.

LU and CC

Under the LU and CC scenarios, in contrast to CLE and MFR scenarios, the results suggest that recovery from acidification will stop and majority of the lakes will decline in ANC over the next 90 years. Much of this decline is apparently due to increased flux of N from catchment soils to surface waters, due to the simulated increased rate of decomposition of soil organic matter. Results from large-scale experiments with increased biomass removal and increased temperature suggest that both changes will result in net decomposition of some of the large pool of soil organic matter characteristic of forests and uplands in Sweden.

LU scenario assumptions and uncertainties

The LU scenario here of maximum removal of biomass from the forest in the future is of course predicated on a series of assumptions. Among these is the assumption that the forest growth in the future will not be limited by shortage of base cations or N, despite the fact that the scenario entails an increased removal of these nutrients from the forest ecosystem. Several studies of forest re-growth following whole-tree harvest, for example, indicate that the new generation trees are depleted in nutrients relative to re-growth following stem only harvest (Thiffault et al. 2006).

CC scenario assumptions and uncertainties

The CC scenario here is also based on a number of assumptions. We assume that the increased temperature will deplete the pool of soil organic C by a constant amount each year. That implies that there the pool of labile organic C is not exhausted after a few years of warmer temperature. We also assume that forest growth will not be limited by shortage of water in the summer, despite the fact that summer temperature is predicted to be higher and that although runoff will increase on an annual basis, probably there will be less runoff (and thus soil moisture) in the summer and more in the dormant season. We have not considered any seasonal variations in this study.

Other factors to be considered

In this study only three effects of future climate change were considered in the simulations; effect of increased temperature on decomposition of soil organic matter, the effect of increased temperature on forest growth and uptake of nutrients from the soil, and the effect of increase runoff on the leaching of solutes from the soil. There are a number of other potential effects of climate change that might affect lake chemistry. Among these are the effect of increased frequency of storms on the deposition of seasalts in near-coastal areas, an increase in base cation weathering due to increased temperature and precipitation, and a change in the concentration of dissolved organic matter in soil solution. Wright et al. (2006) made a modelling study using MAGIC to assess the relative importance of these factors at 14 sites in Europe including the Swedish site Gårdsjön. They showed that while increased decomposition and increased forest growth were important at forested sites, other factors such as seasalt deposition and changed DOC concentrations can also significantly affect runoff chemistry. These other factors were not taken into account in our study, primarily because the quantification of the climate-induced changes is uncertain and thus difficult to implement in MAGIC. However, there are several studies (e.g. White and Blum, 1995, West et al., 2005, Gislason et al., 2008) which in general agree that likely effect of climate change is an increase in chemical weathering rate, which is typically set to between 2 and 10% increase per degree oC increased temperature. This would alleviate acidifying effects of all scenarios by additional release of base cations to the soils. Evaluation of the effects of the increased weathering rate should be considered in potential follow up study.

- **CCLU additive effect assumed, not multiplicative**

We assume that the effects of LU and CC are additive with no synergistic effects. Both will change the rate of decomposition of soil organic matter, and thus the future C pool and CEC of the soil.

- **The results can be used to make a rough estimate of national C budget for Swedish landscape**

These results can be used to make a rough estimate of the effect of climate change and increased biomass removal from the forest on the CO₂ budget for the Swedish landscape. The soils of the lakes included here have on average 830 molC/m² (70 g/m²). This organic matter has been built up since the last ice-age, about 10000 years ago, or roughly 80 mmolC/m²/yr (7 mg/m²/yr). Removal of biomass at present-day using conventional harvesting techniques (stems and 30% of foliage and branches) is estimated to remove about 9.8 mmolN/m²/yr (0.7 mgN/m²/yr), and assuming a C/N ratio in this biomass of about 100 mol/mol, then about 980 mmol/m²C/yr (80 mgC/m²/yr) is removed on average in biomass from the forest. This is about 12 times the average long-term rate of accumulation of C in the soil.

Both the CC and LU scenario (and of course the combined CCLU scenario) entail a net loss of soil organic C because of increased rate of decomposition. The average loss over the 90-year period 2010-2100 was simulated to be 720, 1570 and 2290 mmolC/m²/yr (60, 130, and 190 mgC/m²/yr) for the CC, LU and CCLU scenarios, respectively. These values work out to be 7, 16, and 23 Mt CO₂/yr for 230 000 km² of forest soils in Sweden, and can be compared with the total anthropogenic CO₂ emissions for Sweden of 53 Mt CO₂ in 2004 (<http://hdr.undp.org/en/statistics/data/climatechange/>). The increased C removed in biomass will give no net change in CO₂ budget for Sweden as the source of the C from the atmosphere via photosynthesis and the ultimate fate of the C is back to the atmosphere as CO₂ during combustion of the biomass.

- **The results can be used to make a rough estimate of the increase in N export to the Baltic Sea and Skaggeak**

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