Climate Change and Environmental Objectives

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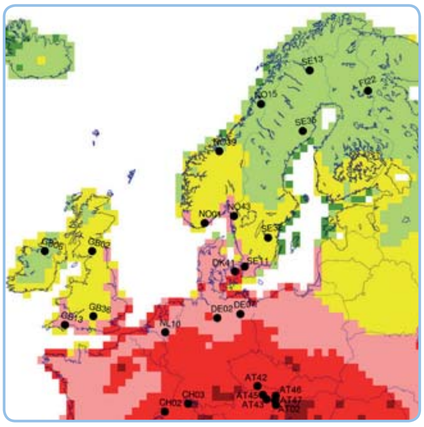

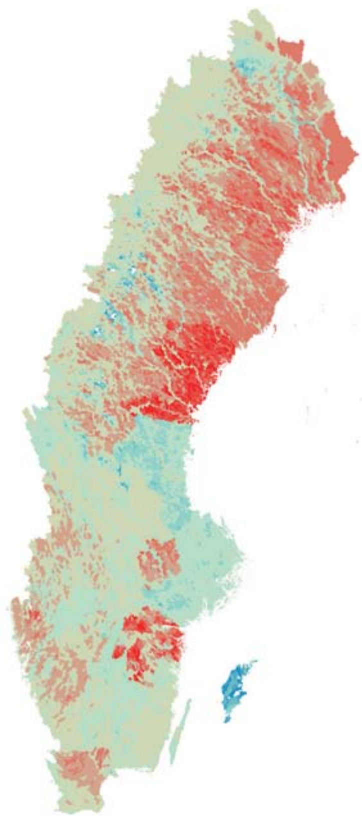

RESEARCH
ENVIRONMENTAL OBJECTIVES

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Climate Change and Environmental Objectives

Synthesis report

SWEDISH ENVIRONMENTAL PROTECTION AGENCY

Orders

Telephone orders: +46 8 505 933 40
Fax orders: +46 8 505 933 40
E-mail: natur@cm.se
Postal address: CM Gruppen AB, Box 110 93, SE-161 11 Bromma, Sweden
Internet: www.naturvardsverket.se/publikationer

Swedish Environmental Protection Agency

Tel: +46 10 698 10 00 Fax: +46 10 698 10 99
E-mail: registrator@naturvardsverket.se
Postal address: Naturvårdsverket, SE-106 48 Stockholm
Internet: www.naturvardsverket.se

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Foreword

The aim of CLEO – the Climate Change and Environmental Objectives research programme – was to quantify how climate change will affect our potential to meet Environmental Objectives that are also affected by long-range transport of air pollutants: *Clean Air, Natural Acidification Only, Zero Eutrophication* and to some extent *A Non-Toxic Environment*. The programme examined changes in the emissions, dispersion and deposition of air pollution, and how the future leaching of acidifying substances and nitrogen and mercury from forest soils into surface water will be affected by climate change. The impact of forestry was also studied, as well as the synergies and conflicts that arise between different abatement strategies for air pollutants and greenhouse gases.

The programme was divided into two phases covering the period 2010 to 2015. In 2014 an interim report was published as a basis for In-depth Evaluation of the Environmental Objectives (FU 2015), which describes the results in more detail (in Swedish). The report is available on the project website www.cleoresearch.se or via www.ivl.se/publikationer.

This report is written by a large number of researchers who contributed to the programme (see back cover). It was edited by John Munthe and Jenny Arnell, IVL Swedish Environmental Research Institute. The authors are personally responsible for the content of the report. The project was funded through an environmental research grant from the Swedish Environmental Protection Agency.

Stockholm, December 2015

Swedish Environmental Protection Agency

Content

Summary

The CLEO research programme – Climate change and Environmental Objectives – was set up in 2010 in response to a call from the Swedish Environmental Protection Agency for research with following general aims:

1. To analyse and quantify how changes in the climate, such as temperature, precipitation and run-off, affect our potential to achieve the Environmental Objectives, which are influenced by long-range transport of air pollution.
2. To describe and analyse synergies and conflicts between national and international measures that aim to reduce emissions of greenhouse gases and other air pollutants in order to achieve the set objectives.
3. To improve our understanding of the underlying processes in order to develop reliable forecasts and scenarios for making progress towards the Environmental Objectives; improve input data for existing models; and enable better integration of models for the climate, air and ecosystems.

The programme focused on the Environmental Objectives of *Clean Air, Natural Acidification Only, Zero Eutrophication* and to some extent *A Non-Toxic Environment.* Because the aim was to produce results that are relevant to ongoing work on Environmental Objectives and long-term planning, CLEO looked at future scenarios that focus on the relatively near future (2030), and in some respects a longer-term perspective (2100).

Scenarios and models

Two regional climate projections from SMHI were used in CLEO, based on ECHAM and HADLEY (two leading global climate models). Average annual temperature and precipitation figures from the projections were adjusted and distributed across Sweden as part of the programme. National Forestry Board scenarios, SKA 08, were used to describe future developments in forestry, with some additions. Mass balances for forest soils were calculated on the basis of forestry scenarios. Historic estimates and projections for emissions of air pollutants are based on the ECLIPSE research programme, supplemented by estimates for 2005–2030 that were made prior to negotiations on a new ceiling directive for emissions of air pollutants within the EU – this scenario is known as CLEO Eurobase.

Various models covering hydrology, bio-geochemical processes and leaching from forest soils into surface water were used to study the effects of climate change and future emissions of air pollutants. The following models were used: MATCH, HYPE, CoupModel, MAGIC, PROFILE, RIM, FLUXMASTER, NET and ForSAFE.

Emissions, concentrations and deposition of air pollutants

Future deposition of air pollutants over Sweden is affected by emission levels, mainly in Europe, as well as shipping and changes in the climate. Climate change plays a smaller role, but does affect factors such as precipitation levels and atmospheric residence times, and hence the distance air pollutants are transported. The residence times for sulphur dioxide and nitrogen oxides are expected to increase due to climate change, but decrease for ammonia. This means that ammonia emissions will be deposited closer to their sources in the future.

Concentration of ground-level ozone

Peak levels of ozone have fallen, while background levels have risen. Ozone concentrations are highest over the sea. If emissions of ozone precursors decrease as forecast by 2050 it is calculated that ozone impact on vegetation, measured as AOT40, will not exceed the threshold values set out in the Convention on Long-range Transboundary Air Pollution (LRTAP). However, if ozone flux is used as a criterion the current threshold values will continue to be exceeded over southern Sweden. Emissions of ozone precursors such as nitrogen oxides have a greater influence on future levels than climate impact and rising background levels.

Particles

The calculated change in anthropogenic emissions between 2005 and 2030 is expected to lead to a reduction in particles measured as PM2.5, by around 20 per cent in Götaland and parts of Svealand. The reduction in northern Sweden is expected to be less than 10 per cent.

Small-scale wood combustion is now the largest single contributor to emissions of particles from combustion in Sweden. The CLEO programme has contributed to the development of a module for modelling particle formation and dispersion, which has made it possible to develop better future forecasts for particle levels.

Risk of nitrogen leaching

There are currently forest areas with elevated levels of nitrogen leaching, primarily in south-west Sweden. A sensitivity analysis covering changes in climate, forestry and nitrogen deposition (not from fertiliser) shows that climate change will have a greater impact on nitrogen leaching from forest soil than airborne deposition and forestry. Reduced nitrogen deposition does not however always lead to less risk of nitrogen leaching. Increased biomass extraction can reduce the risk of nitrogen leaching from areas that are at risk of nitrogen leaching and favour *Zero Eutrophication*, while the use of nitrogen fertiliser can have a negative effect. By the year 2050 it is calculated that climate change and increased biomass removal will not have any significant effect on nitrogen leaching.

Recovery from acidification

The deposition of acidifying substances has affected the acidity of soil, surface water and groundwater over a long period. Acidification impact was greatest at the end of the 1980s, but there has been a strong regional recovery since then, and the percentage of acidified lakes and waterways has fallen. In the short term, until 2030, this recovery is expected continue even with increased biomass removal, but in the longer term, forestry could have a negative impact on recovery. A model was applied to the soils surrounding 2,631 lakes. In 2010, there was an annual net increase in calcium reserves and thus recovery of base saturation in the surrounding soils at 22 per cent of the modelled sites. In 2030, the proportion of lakes with rising exchangeable calcium in the soil rises to 30 per cent and 26 per cent respectively for the BUS and MBR forestry scenarios, which indicates continued recovery from acidification. However, the proportion of catchment areas with rising calcium reserves drops to 18 per cent for the most intense forestry scenario, HBR, which shows a risk of delayed recovery, and in the worst case re-acidification. According to scenario calculations up to 2050, recovery is affected by both climate change and increased biomass removal from forests, with forestry having the greatest influence. The main impact of climate change is increased precipitation, which can lead to greater run-off and increased leaching of substances such as dissolved organic Carbon (DOC), and through temperature rise, which accelerates weathering. By 2050 it is calculated that there will be a moderate rise in DOC concentrations in waterways, mainly in northern Sweden.

Leaching of mercury

Mercury levels are still too high in roughly half of Swedish lakes. Forestry may also have a negative effect and lead to an increase of up to six per cent in the mercury load in surface water, which could result in higher concentrations of mercury in fish. Climate change may have an impact by leaching out mercury as a result of increased precipitation and run-off. Extreme precipitation may lead to additional, local leaching of mercury, mainly in the form of methyl mercury.

Synergies and conflicts between environmental quality objectives

The report describes the synergies and conflicts that may arise when various measures are taken to reduce air pollutant emissions, and gives advice on how these may be managed. Many of the methods that have been implemented to limit climate gas emissions or air pollution emissions also favour other environmental quality objectives. Examples include EU directives for transport, energy efficiency or reducing methane emissions. In some cases however there will be conflicts, where measures that target one environmental objective will have negative effects on another. For example, around half of the 1.3°C temperature rise reported so far in the Arctic may be due to a reduction in sulphur emissions in Europe, since sulphur particles have a cooling effect. Because Europe now has much lower emissions of sulphur than in the 1970s, further reductions in emissions of sulphur ought to have very little effect on the climate.

Harvesting of branches and tops of trees is desirable to replace fossil fuels and meet the objective of *Limited Climate Impact*, and may also reduce the risk of accelerated nitrogen leaching, but also entails a risk of conflict with *Natural*

Acidification Only by increasing the removal of alkaline substances, and with *A Non-Toxic Environment* by increasing the risk of damage by forestry machinery and hence the risk of mercury leaching. Increased combustion of biofuels can lead to higher emissions of particles, PM2.5, especially through small-scale wood burning.

Abbreviations and terminology

A1B	Global emission scenario for CO_2 and other climate-forcing agents.
ANC	Acid neutralizing capacity
AOT40	Ozone measurement for accumulated ozone dose over 40 ppb
BAG	Fertilisation according to the needs of the stands
BUS	(BUSiness as usual) one of three scenarios for future forestry in Sweden covering the period 2010 to 2100: representing current forestry practice
CH_4	Methane
CLE	Current legislation
CLEO	Climate change and Environmental Objectives
CLEO Eurobase	An emission scenario developed in phase 2 of CLEO
CO	Carbon monoxide
CoupModel	Dynamic model for nitrogen and carbon turnover in terrestrial ecosystems
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
ECHAM	Global climate projections/model
ECHAM5_A1B3	A global climate projection developed using the ECHAM5 model. This projection is based on the A1B emission scenario and "initial conditions 3". The abbreviation is also used for the regional downscaling of this climate projection.
ECLAIRE	The EU project *Effects of Climate Change on Air Pollution and Response Strategies for European Ecosystems*
EMEP	*The European Monitoring and Evaluation Programme*
EU NEC IA option 1	The EU Commission's base scenario (which formed the basis for the European Commission's proposal for a new Emission Ceilings Directive)
ForSAFE	Dynamic ecosystem model for studying carbon and nutrients in soil
FLUXMASTER	Model for studying hydrology and substance transport in small catchment areas
FU15	In-depth evaluation of environmental objectives 2015
GIS	Geographical information systems/maps
GROT	Branches and tops of trees
HADLEY	Global climate projections/model
HBR	Forestry scenario (High Biomass Removal)
HYPE	Large-scale hydrological model

LBR	Forestry scenario (Low Biomass Removal) that entails reduced removal of forest residue by 30 per cent
MAGIC	Model for studying acidification and recovery
MATCH	Model for calculating the dispersion and deposition of air pollution and the exposure of vegetation to ozone
MBR	(Medium Biomass Removal) that entails increased removal of forest residue, but with environmental restrictions
meq, µeq	Milli- and micro-equivalents. An equivalent is a unit of measurement of the amount of a substance corresponding to one mole of charge. 1 meq = 1000 µeq
NET	Upscaling tool
NH_3	Ammonia
NMVOC	Volatile hydrocarbons
NOX	Nitrogen oxides
PM10, PM2.5, PMBC, PMOC	Particles (≤10µm, ≤2.5 µm, black carbon, organic carbon)
PROFILE	Model for studying weathering in forest soil
RCP4.5	One of the UN Climate Panel's (IPCC) scenarios for future climate change
SKA VB-08	Forestry impact analyses and wood balances 2008
SLCF/SLCP	Short-lived climate forcers/pollutants
SOX (SO_2)	Sulphur oxides, sulphur dioxide
Total-N	Total nitrogen
VOC	Volatile organic compounds

A research programme for studying environmental objectives in a changing climate

Facts about CLEO

Swedish title: Klimatförändringen och Miljömål
English title: Climate Change and Environmental Objectives
Funded by: The Swedish Environmental Protection Agency
Duration: 2010–2012 (phase 1), 2013–2015 (phase 2)
Website: www.cleoresearch.se
Participants: IVL Swedish Environmental Research Institute (coordinator), the Swedish Meteorological and Hydrological Institute, University of Gothenburg, Stockholm University, Lund University, the Swedish University of Agricultural Sciences

Background

The Climate change and Environmental Objectives programme – CLEO – was set up in 2010 in response to a call from the Swedish Environmental Protection Agency for research with the following overall aims:

1. To analyse and quantify how changes in the climate, such as temperature, precipitation and run-off, affect our potential to achieve the environmental objectives that are influenced by long-range transport of air pollution.
2. To describe and analyse synergies and conflicts between national and international measures that aim to reduce emissions of greenhouse gases and other air pollutants in order to achieve the set objectives.
3. To improve our understanding of the underlying processes in order to develop reliable forecasts and scenarios for making progress towards the Environmental Objectives; to improve the input data for existing models; and to enable better integration of models for the climate, air and ecosystems.

The programme focused on the Environmental Objectives of *Clean Air, Natural Acidification Only, Zero Eutrophication* and to some extent *A Non-Toxic Environment.* The potential for achieving these objectives is affected by the long-range transport of air pollutants from emission sources outside Sweden, and climate change is also expected to have an effect. The impact of air pollutants, climate change and forestry on environmental objectives other than those mentioned above is not covered by the programme. After evaluating the first phase of CLEO, slightly more emphasis was placed on the impact of forestry on the potential to achieve the Environmental Objectives.

This report gives a summary of a selection of research results from the programme. A more complete picture of the results is provided in the report submitted by the CLEO programme for the in-depth evaluation of Environmental Objectives 2015 (FU15), and other reports and publications that are available on the CLEO website www.cleo research.se/publications.

Environmental objectives in a changing future – driving forces

Environmental objectives and research questions for the CLEO programme

Clean Air: The air must be clean enough not to represent a risk to human health or to animals, plants or cultural assets.

- Research questions for CLEO: How will the dispersion and deposition of air pollutants change as the climate changes in the future, and how will future emission changes affect levels of air pollutants in Sweden? How will the effects of ozone on vegetation change?

Natural Acidification Only: The acidifying effects of deposition and land use must not exceed the limits that can be tolerated by soil and water. In addition, deposition of acidifying substances must not increase the rate of corrosion of technical materials located in the ground, water main systems, archaeological objects and rock carvings.

- Research questions for CLEO: How will the ongoing recovery of acidified surface water be affected by future deposition changes, climate change and changing forestry? Will the leaching of acidifying substances from forest soils be affected?

Zero Eutrophication: Nutrient levels in soil and water must not be such that they adversely affect human health, the conditions for biological diversity or the possibility of varied use of land and water.

- Research questions for CLEO: How will the leaching of nitrogen from forest soils into surface water be affected by deposition changes, climate change and changes in forestry?

A Non-Toxic Environment: The occurrence of man-made or extracted substances in the environment must not represent a threat to human health or biological diversity. Concentrations of non-naturally occurring substances will be close to zero and their impacts on human health and on ecosystems will be negligible. Concentrations of naturally occurring substances will be close to background levels.

- Research questions for CLEO: How will the leaching of mercury from forest soils into surface water be affected by climate change and changes in forestry?

Synergies and conflicts between the environmental objectives.

- Research questions for CLEO: How do the various measures for reducing emissions of greenhouse gases and air pollutants interact? How does growing use of forest biomass affect acidification, eutrophication and mercury levels in forest soils and surface water? How do acidification and eutrophication affect forest ecosystem services?

What factors will affect the Environmental Objectives in the future?

The Swedish Environmental Objectives system sets one generational goal, 16 environmental quality objectives and 24 milestone targets. The generational goal defines the changes in society that are needed within one generation to achieve the environmental quality objectives, while the environmental quality objectives describe the state of the Swedish environment that environmental action shall lead to. The milestone targets describe steps that Sweden can take on the way to achieving the generational goal, as well as one or more environmental quality objectives. More information about the Environmental Objectives, definitions and milestone targets can be found at www.miljomal.se/

Our ability to achieve the Environmental Objectives is affected by a number of factors, including air pollutant emissions, which affect all the environmental quality objectives covered by CLEO. Climate change is also expected to affect our potential to achieve the Environmental Objectives, as will changes in forestry. Increased use of forest biomass to produce energy and materials to replace fossil fuels is an important factor in efforts to combat climate change. Changes in practices and more intensive forestry may however support or counteract the achievement of environmental quality objectives.

Methods used in CLEO

To examine how the environmental status of the air, soil and water are affected by future climate change we need future scenarios that describe as accurately as possible how a range of influencing factors may change. CLEO involved compiling and developing a number of scenarios covering climate, air pollutant emissions in Europe, and the way that forest growth and forestry practices are expected to change in the future. These scenarios were adapted and developed to provide a basis for modelling and evaluating the scientific questions asked in the programme.

Forestry scenarios

Three scenarios for future forestry in Sweden were formulated for the period 2010–2100: BUS (BUSiness as usual), which corresponds to current forestry practices; MBR (Medium Biomass Removal) corresponding to increased extraction of biomass but with environmental restrictions, and HBR (High Biomass Removal), which corresponds to significantly increased extraction of biomass. All the scenarios allow for increased forestry in the future, with more biomass extraction from the forest, including stems, branches and tops, and stumps. No land use changes are included in the BUS or MBR scenarios during this century, but the HBR scenario includes an increase in the area of productive forest soils through afforestation of arable land. Growth-enhancing measures, and in particular climate change, lead to increased growth and harvesting in all three scenarios from 2020 onwards. Stem yield from felling (tons of dry matter) is expected to rise by 45 per cent with BUS, 62 per cent with MBR and 70 per cent with HBR, between 2010 and 2100. All the forestry scenarios are based on information from Swedish Forest Agency reports on future growth scenarios and wood balances, SKA VB-08, (Swedish Forest Agency, 2008) supplemented by data on stump removal, fertilising, liming and ash recycling. The effects of climate change on forest growth are included in all the scenarios.

Climate scenarios

Two climate projections are used in CLEO: ECHAM and HADLEY (alternative global climate models). These have been shown to match relatively closely the spread of existing climate projections based on future changes. By the middle of the century the projections show an increase in mean annual temperature by around 2–2.5°C for ECHAM, and by a further 1°C for HADLEY. The increase is greater in northern than in southern Sweden. By the end of this century the increase for both the projections is between 3.5 and 5°C, again with the largest increase in the north. According to the HADLEY projection the mean annual precipitation will increase by 150–300 mm over the mountain chain by the middle of the century. The corresponding increase for south-east Sweden is 50–100 mm/year. The ECHAM projection gives a considerably smaller rise on the whole, and in western Sweden indicates no change from current levels. By the end of the century both projections show larger increases, with up to 400 mm in northern Sweden and 50–200 mm in southern Sweden. To enable their use in hydrological models a number of meteorological parameters were modelled with higher resolution than available in the original scenarios. This was done with the aid of statistical methods that were refined as part of the research programme.

Emissions of air pollutants

CLEO involved using two different emission scenarios to calculate levels of air pollutants across Europe. Initially we used emission data based on the RCP4.5 scenario. At a later stage we developed our own scenario, *"CLEO Eurobase"*, which was adapted in line with the EU Commission's proposal for a new Emission Ceilings Directive. The purpose of *CLEO Eurobase* was to produce policy-relevant, sectoral and air-pollutant-specific emissions paths for 10 categories of air pollutants covering the period 1960–2100, with a 50 km × 50 km geographical resolution. *CLEO Eurobase* provides annual emissions of SOX (SO_2), NOX, CO, NMVOCs, NH_3, CH_4, PM10, PM2.5, PMBC, PMOC and coarse particles for the period 1960 to 2100. Emission data was compiled from the EU project ECLAIRE, the EU Commission's baseline scenario EU NEC IA option 1, the Nordic ENSCLIM project and the EU project ECLIPSE. Gaps in the data were filled by interpolation.

Models

A number of models and tools were used to study the effects of climate change and future emissions of air pollutants. The models describe how conditions and processes in the air, forests and surface water are affected by climate change, changes in forestry and changes in emissions of air pollutants. The way these models were used is described in the respective sections below. To ensure that the results from the models are comparable and compatible, the same basic assumptions were used wherever possible in areas such as hydrology, climate and forestry. The models used for the CLEO programme are presented briefly in Table 1.

Table 1. *Models used in the CLEO programme.*

Model	Application	Reference
MATCH	For calculating the dispersion and deposition of air pollutants, and the exposure of vegetation to ozone	Langner et al. 2012; Engardt and Langner, 2013; Klingberg et al. 2014
CoupModel	Nitrogen and carbon turnover in terrestrial ecosystems	Jansson 2012, Jansson and Karlberg 2004
HYPE	Large-scale hydrological model	Lindström et al. 2010, Strömqvist et al. 2012
MAGIC	Acidification and recovery	Cosby et al. 2001, Moldan et al. 2013
FLUXMASTER	Hydrology and substance transport in small catchment areas	Schwarz et al. 2006, Hytteborn et al. 2015
PROFILE	Weathering in forest soils	Sverdrup and Warfvinge 1993
RIM	Substance transport in small catchment areas	Eklöf et al. 2015a, Winterdahl et al. 2011
NET	Upscaling tool	Developed for CLEO
ForSAFE	Base cations, nitrogen and carbon in soil	Wallman et al. 2005

Models were used in combination with measurements to quantify the combined effects of climate change, atmospheric deposition and forestry on soil leaching and acidification throughout Sweden.

Environmental data

Research for CLEO primarily took the form of synthesis with the aid of various models. An important part of this work was harmonising input data for the various models and linking their results. This research could not have been carried out without measurement data from studies on air, soil and water. CLEO only generated a small amount of new environmental data, but instead used data from previous and ongoing research, and from international, national and regional environmental monitoring. A large part of the environmental data that was used is available from a public database at www.slu.se/Cleo/data.

From emissions to environmental effects

Emissions of air pollutants

Historical estimates and projections of future emissions of air pollutants – essential for modelling transport, deposition and effects – were compiled in the *CLEO Eurobase* scenario. This is based on the European scenarios that form the basis for the ongoing review of EU air policy (national total emissions during the period 2005–2030), but is supplemented with results from European research programmes to enable annual regional emission allocations for the entire period 1960–2100.

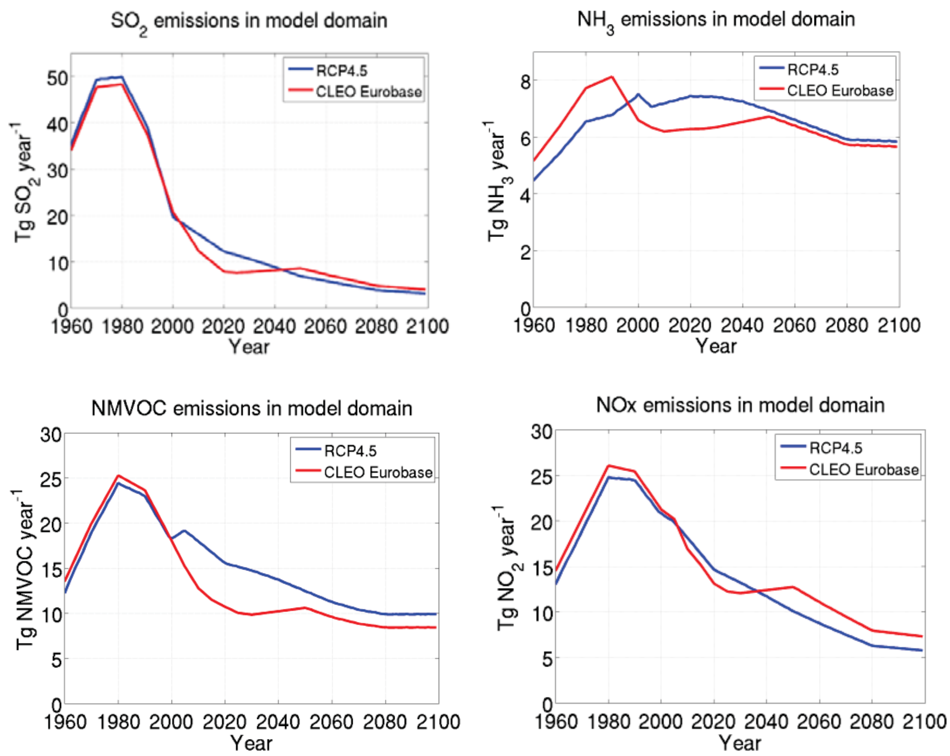


Figure 1. *Total emissions of sulphur dioxide (SO_2), ammonia (NH_3), volatile hydrocarbons (NMVOCs) and nitrogen oxides (NOx) in the geographical area covered by the MATCH model. The two curves represent the different emission estimates used by CLEO, RCP4.5 (phase 1) and CLEO Eurobase (phase 2).*

Figure 1 shows emissions of a selection of air pollutants summarised over an area that covers Europe, parts of North Africa and parts of the North Atlantic. The graphs compare total emissions for the period 1960–2100 in *CLEO Eurobase* with emission data from RCP4.5 for the same area.

It is clear that emissions of most air pollutants in Europe have declined considerably since the end of the 1970s. The downward trend is expected to continue for a few more years, and then flatten out. *CLEO Eurobase* indicates higher emission reductions for several of the air pollutants than the RCP4.5 scenario that was previously used. The main differences between RCP4.5 and *CLEO Eurobase* are for NH_3 and NMVOCs, which are more difficult to estimate than SO_2 and NO_x for example. In the case of NH_3 the emission curve is almost entirely dependent on future development in the agricultural sector. *CLEO Eurobase* indicates that NH_3 emissions will fall between 1990 and 2010, then increase slightly up to 2050.

Concentrations of ground-level ozone

Ozone concentrations in rural areas of northern Europe over the last twenty years or so show a pattern of falling ozone peaks, but rising low and median levels, see Figure 2. The rising low and median levels are probably explained by a general increase in ozone levels across the northern hemisphere.

Ozone levels in urban regions show a somewhat different trend. A comparison of trends in average ozone levels in urban and rural areas of the west coast over the period 1997–2010 (Pleijel et al., submitted paper) does not reveal any significant trend for Råö, a rural location south of Gothenburg, while there was a significant upward trend in the dense urban area of central Gothenburg. It is likely that this urban increase in ozone level is explained by falling emissions of nitrogen oxides, and thus reduced breakdown of ozone by nitric oxide. NO_2 concentrations in Gothenburg fell slightly but significantly over the period.

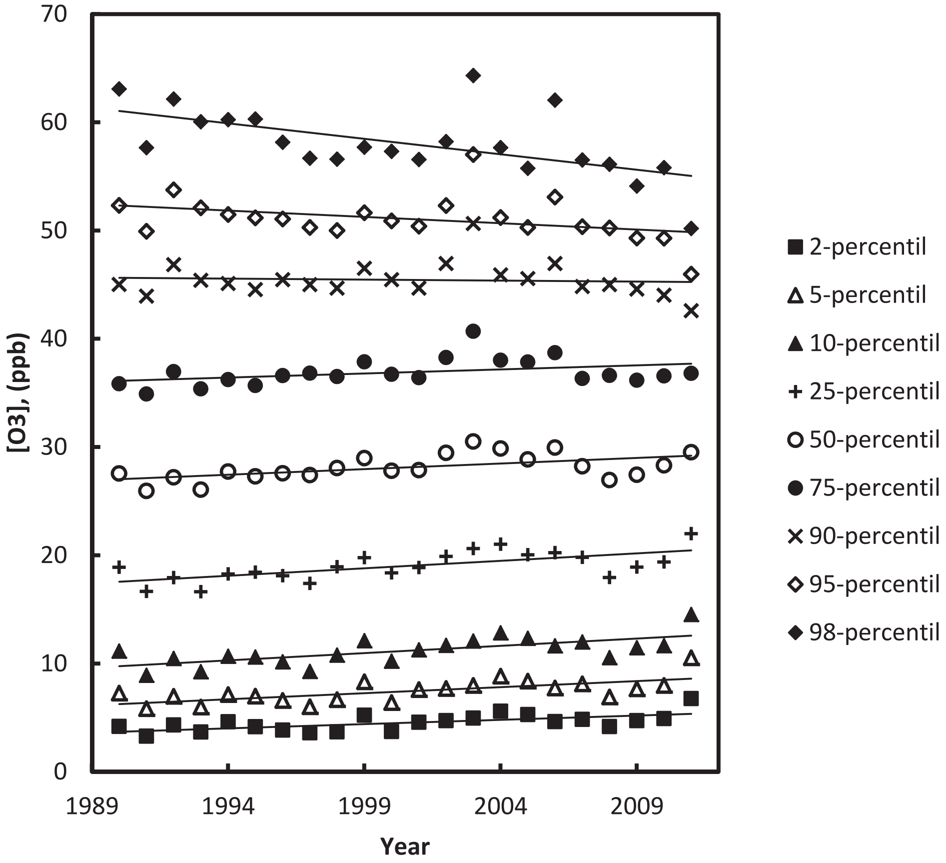


Figure 2. *An overview of percentile trends for ozone concentration between 1990 and 2011 for 25 locations in Europe north of the Alps. The locations of the sites are shown in Figure 3. The 95th percentile, for example, is the level that is exceeded 5% of the time (based in this case on hourly average values). The 50th percentile is the median and is the typical value that is exceeded or not reached for equal lengths of time. The downward trend for the 98th percentile (peak levels) and the rising trends for the 2nd, 5th, 10th, 25th and 50th percentiles are statistically significant. Unpublished data (Klingberg, Pleijel and Karlsson).*

Future effects of ozone on vegetation and human health are due to a combination of changes in emissions of ozone precursors and climate change. If European emissions of ozone precursors fall as indicated by the *CLEO Eurobase* scenario up to the year 2050 it is calculated that most relevant ozone measurements will fall in Sweden. Figure 3 shows, for example, that the target value for the protection of vegetation based on AOT40 (accumulated ozone dose over 40 ppb, where ppb = parts per billion in air) from April to September – 5000 ppb hours – will no longer be exceeded in Sweden, nor in large parts of northern Europe. Future exposure of vegetation to ozone, calculated as ozone flux, i.e. ozone uptake by plants, will nevertheless continue to exceed the target value set by the LRTAP convention (Klingberg et al. 2014).

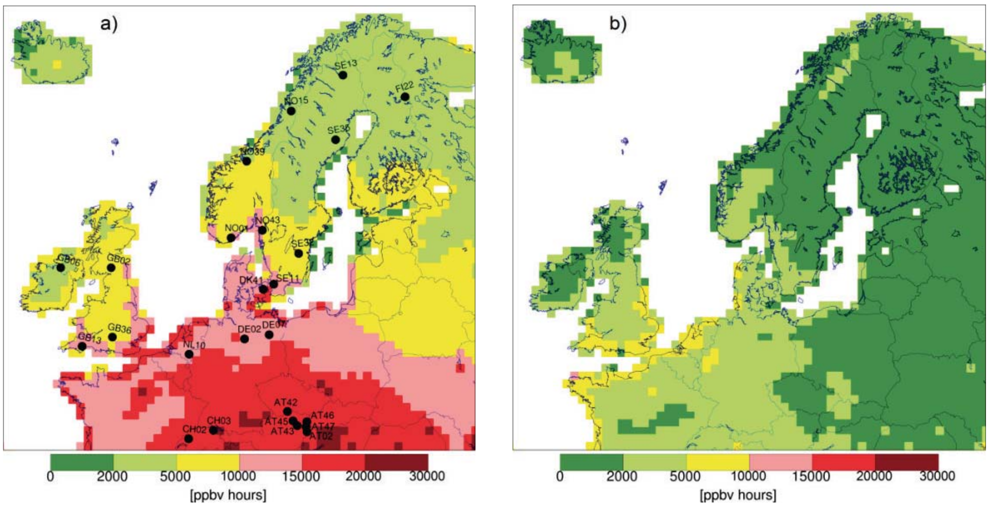


***Figure 3**. Calculated AOT40 during the period April to September. (a) average value for the period 1990–2009. (b) average value for the period 2040–2059. In both cases the MATCH transport model used meteorological data for each period from a downscaling of model results based on an A1B scenario with the regional climate model RCA3. (a) also shows which stations provided the data used in Figure 2. This diagram is based on Fig. 3 in Klingberg et al. (2014).*

The reduction in AOT40 and other relevant ozone measurements in Europe is due mainly to changes in emissions of ozone precursors within European borders. Climate change and rising background levels of many substances in the northern hemisphere naturally cause significant changes in ozone levels, but these changes are usually much smaller than those caused by emission changes. When the change in 24-hour peak ozone levels in summer between 2000 and 2050 is modelled solely on the basis of climate change, ozone concentrations over Sweden only change marginally. If the modelled change is instead based on both climate change and falling emissions of ozone precursors, there is a considerably larger fall in ozone levels, of up to 9 ppb in southern Sweden. Figure 4 shows the modelling results for changing daily peaks (from April to September) in ozone levels from 2000 to 2050.

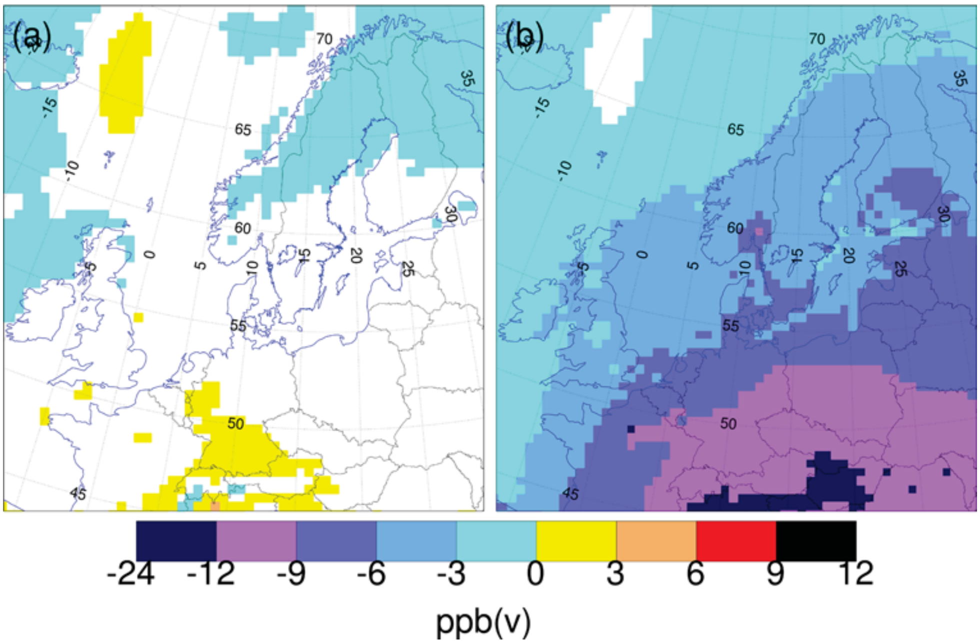


***Figure 4.** Modelled change in daily peak (from April to September) in ozone levels from 2000 to 2050. (a) shows the effect of climate change alone (ECHAM5_A1B3). (b) shows the effects of climate change as in (a), combined with the trend in ozone precursor emissions for the model domain in line with RCP4.5. Non-significant changes are shown in white. This diagram is based on Fig. 4 in Langner et al. (2012).*

Particles

The assumed change in anthropogenic emissions between 2005 and 2030 (*CLEO Eurobase*) are calculated to lead to a clear reduction in PM2.5 levels throughout Sweden, see Figure 5. In Skåne, the reduction is about 2 µg/m^3 (around 30%) and in the whole of Götaland and parts of Svealand it is greater than 1 µg/m^3 (around 20%), while the reduction in the north of Sweden is less than 0.5 µg/m^3 (around 10%).

Background levels of PM2.5 in Sweden are calculated to vary from about 7 µg/m^3 in Skåne to approximately 2 µg/m^3 in Jämtland. The main components of PM2.5 are sulphates (about 20%) and organic substances (about 35–50%). The organic fraction is complex, and a model description of emissions and atmospheric processes was developed in CLEO to permit a more accurate representation of this fraction.

Wood burning is by far the main anthropogenic source of organic particles in Europe. New European inventories of wood-burning emissions by the Dutch research institute TNO indicate that this source has been greatly underestimated so far (in the case of Sweden only around one-third of actual emissions are estimated to be accounted for). The large degree of uncertainty surrounding wood-burning emissions means that estimated changes in PM2.5 are also uncertain. This applies in particular to future levels of organic particles.

Emissions of volatile organic hydrocarbons from European forests lead to the formation of biogenic organic particles. There are a number of question marks about how these biogenic emissions will change with climate change. Increased insect attack on trees could for example lead to significant increases in stress-induced emissions of particulate matter and hence rising levels of secondary organic aerosols.

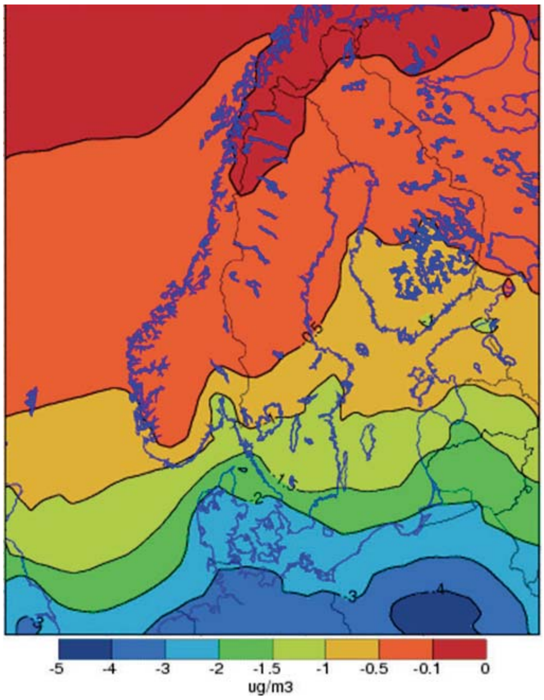


Figure 5. *Calculated difference in concentrations of PM2.5 emissions between 2030 and 2005. Values solely reflect changes in emissions, and therefore do not take into account changes in climate. Unit: $\mu g\ m^{-3}$.*

Deposition of nitrogen and sulphur

Future deposition of air pollutants is affected by both emission levels and changes in climate. Changes in the deposition of sulphur and nitrogen over Sweden up to 2050 will primarily depend on changes in emissions in the rest of Europe. Climate change plays a smaller role, even though it affects the residence time of air pollutants in the atmosphere, and hence how far sulphur and nitrogen are transported in Europe.

Considering Europe as a whole, it is estimated that the deposition of sulphur and oxides of nitrogen will decrease by around 60 per cent and 40 per cent respectively between 2000 and 2050. According to *CLEO Eurobase,* emissions of NH_3 will not however fall to the same extent, so the deposition of reduced nitrogen will be largely unchanged, and show a slight increase close to the source locations. This local increase is due to the fact that atmospheric levels of sulphate and nitric acid will fall sharply, resulting in reduced formation of particles with ammonia, and thus affect long-range transport.

As part of CLEO and the associated EU project ECLAIRE we also compared the MATCH model with the EMEP model and observations covering a longer period. Figure 6 shows a comparison of the average concentrations of sulphate, nitrate and ammonium precipitation in Sweden over the period 1955–2011 for both models, together with quality-controlled observations. The figure shows that the models give similar results, but also that they underestimate the concentration of sulphates in precipitation during the 1960s and early 1970s. The levels of sulphate, nitrate and ammonium in Swedish precipitation show a downward trend for at least the past two decades. In the case of the observed deposition levels of the two forms of nitrogen, other studies indicate that the trends are not so clear (Hansen, et al., 2013).

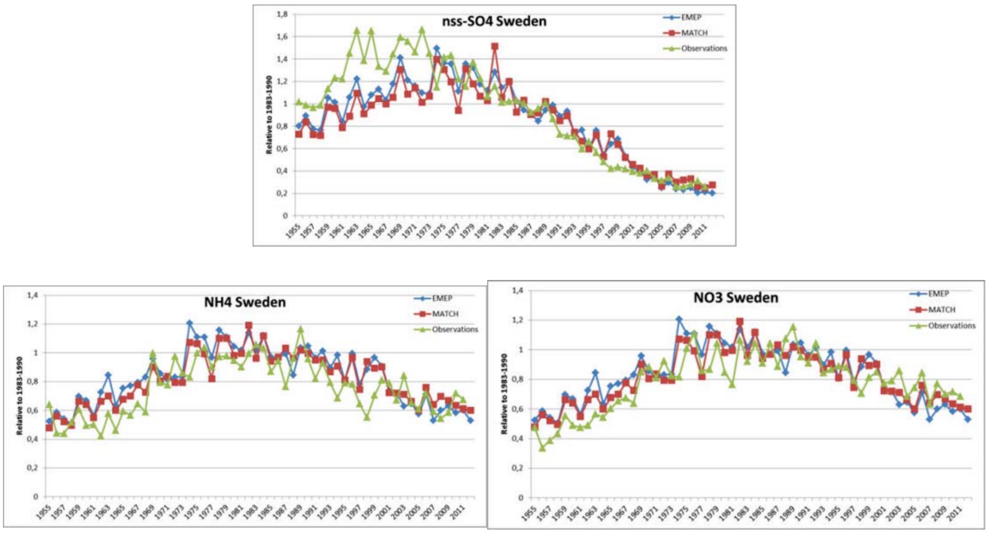


Figure 6. *Comparison between observed and calculated (using MATCH and EMEP models) relative changes in the concentrations of sulphate, nitrate and ammonium in precipitation for the period 1955 to 2011. Unit: relative change compared to mean value for the period 1983–1990. nss-SO4 indicates that the content of sulphate in precipitation was calculated after excluding the contribution from sea salt.*

Sulphur, acidification and recovery

The transport and leaching of substances have a strong influence on chemical conditions in soil and water, and thus on terrestrial and aquatic organisms. The aquatic environment includes everything from soil-water and groundwater, through small forest streams, to lakes and large rivers that eventually feed into the sea. Soil refers to the ground covering the entire catchment area, but for the purposes of CLEO we focused mainly on forest soils. Current and future leaching is affected by three main factors: climate, land use and air pollution. The relative importance of these factors is not easy to quantify or generalise, since so many processes are involved and they are connected by many different links and feedback loops.

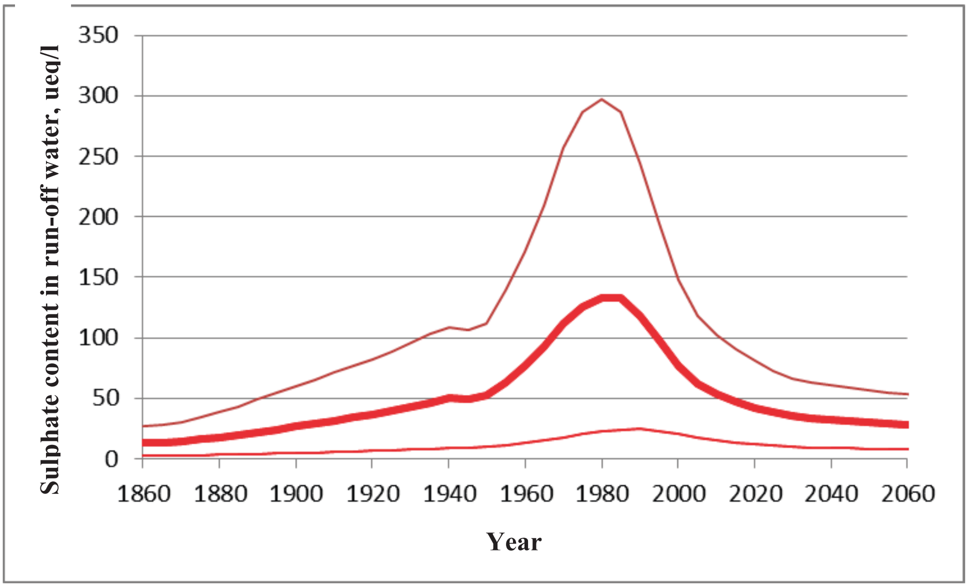


Figure 7. *Change in sulphur concentration in surface water over time, modelled using MAGIC model for 2,631 lakes in Sweden. The heavy line shows the mean value, while the two thin lines indicate the concentrations in lakes with the highest 10% and lowest 10% of loadings respectively (Moldan et al., 2013).*

The deposition of acidifying substances is currently well below the highest levels observed in the 1980s and early 1990s, and there has been significant recovery of acidified systems. The concentration of sulphur in surface water has mirrored the trend in sulphur deposition, with some delay, as illustrated by the modelled sulphur concentrations in surface water in Figure 7. Leaching of sulphate leads to soil and water acidification, as it decreases the buffering capacity of soil in the form of exchangeable base cations, so the acidity of soilwater, groundwater and surface water rises. The concentration of sulphate in run-off water rose by several hundred per cent in the second half of the 20th century, and sulphur deposition was the single largest cause of acidification at that time. Forestry entails the removal of base cations from the soil, since cations are taken up by trees as they grow, incorporated into their biomass and harvested during felling. Forestry had a relatively minor influence during the period of high sulphur deposition. Today's situation is very different; sulphate levels have fallen sharply since 1990 and base cation leaching has decreased at the same rate. Forestry has now become a much more significant factor in the acidification context because of the reduction in sulphur deposition, but also because the modernisation and intensification of forestry now means that more biomass is harvested.

Modelling future changes in acidification would be relatively easily if air pollution was the only driving factor. We now have a good understanding of acidification processes thanks to the extensive research undertaken when the problem of acidification began to attract attention over 30 years ago. But we still the face the question of how recovery will be affected by future climate change, in combination with forestry and the remaining atmospheric deposition levels.

Future developments were modelled using the MAGIC acidification model (Cosby et al., 1985; 2001), with input data calculated for three forestry scenarios (BUS, MBR and HBR), one deposition scenario (current legislation, CLE) and two climate projections (based on ECHAM and HADLEY respectively).

Future climate projections indicate a gradual change in precipitation and water supply, as well as rising temperature. A further climate-related factor is mineral weathering from soil. Future temperature rises could increase the rate of weathering, which in turn would accelerate recovery (or counter re-acidification) by enabling faster restoration of base cation reserves in soil. To account for this, the change in the weathering rate due to rising temperature was calculated using the PROFILE model (Sverdrup and Warfvinge, 1993), and these results were then input into the MAGIC model.

Future recovery from acidification

In the short term, up to 2030, recovery from acidification will continue under all forestry scenarios and climate projections developed in CLEO. The buffering capacity of water expressed as ANC (Acid Neutralising Capacity) will increase most in lakes that are most vulnerable to acidification. In lakes with an ANC of around 30 µeq/l in 2010, the buffering capacity will rise on average by 6 to 8 µeq/l by 2030, depending on the forestry scenario and climate projection used. The modelling results for ANC are presented in Table 2. On average, the ANC of lakes will rise by 2 to 4 µeq/l. Looking further ahead, the differences between scenarios will be slightly larger. By 2050, the two more intensive forestry scenarios will in many cases lead to mild re-acidification compared with their status in 2030. Under the BUS scenario, recovery will level off or continue weakly, according to the climate projection based on ECHAM. But when BUS is combined with the climate projection based on HADLEY, it will lead to a slight re-acidification compared with 2030. The differences between the scenarios become even clearer the further ahead we look. Toward the end of the century, the HBR scenario will lead on average to a deterioration in water quality compared with both 2010 and 2030. For the BUS and MBR scenarios, the results for 2100 vary, depending on how weathering is dealt with and which climate projection is used, see Table 2. This applies to both the average for all lakes and to those lakes that are most vulnerable to acidification, where the risk of biological damage is highest.

Differences in leaching of acidity and alkalinity between the three forestry scenarios are relatively small up to 2030. The main reason is that 20 years (2010–2030) is a relatively short period of time in relation to the small annual changes that the forestry scenarios entail.

Table 2. *ANC (μeq/l) in surface water calculated with the MAGIC model for different years and scenarios. S=forestry and V=change in weathering. The results refer to the average of 2,631 lakes scattered throughout Sweden.*

		2030			2050			2100			**2010 (observed)**
Forestry		**BUS**	**MBR**	**HBR**	**BUS**	**MBR**	**HBR**	**BUS**	**MBR**	**HBR**	
ECHAM	S+V	168	167	166	169	168	165	170	166	155	164
	S	168	167	166	168	166	163	163	158	147	
HADLEY	S+V	167	167	166	166	165	162	167	163	152	164
	S	167	166	165	164	163	160	159	155	143	

This can be illustrated with the mass balance for calcium, shown in Figure 8. The annual addition of calcium from weathering and deposition, and the annual loss through leaching and uptake by trees, both average just over 60 meq/m^2/year. The BUS scenario leaves just under 2 meq/m^2/year for the restoration of base cation saturation in the soil, which will lead to recovery in the long term. The HBR scenario causes an annual loss of slightly less than 4 meq/m^2/year and therefore leads to slow re-acidification. One additional factor that contributes to the slow impact of ANC is that the reserve of interchangeable base cations is relatively large (typically between 10,000 and 20,000 meq/m^2 in Swedish forest soil) and changes slowly.

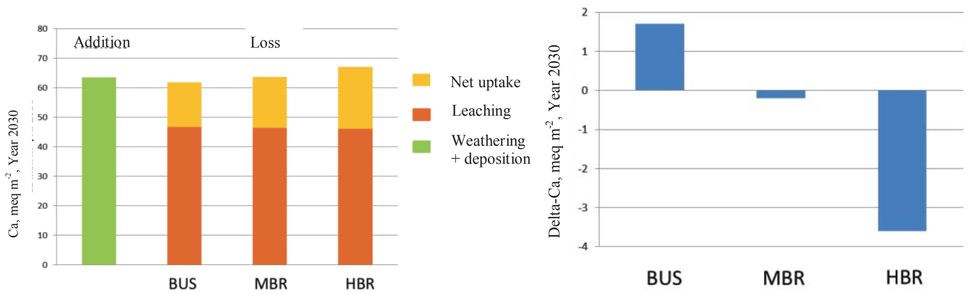


Figure 8. *The addition and loss of calcium (Ca) under the different forestry scenarios and the HADLEY climate projection. Diagram on left: Addition from weathering and deposition, and loss through net uptake and leaching, Diagram on right: difference between additions and losses of calcium (meq/m^2) for the year 2030.*

Even though the *average* differences in the mass balance of base cations are relatively small, the influence of the various forestry scenarios on the development of the individually modelled lakes is in some cases considerable. The average response conceals lakes that have good potential to continue recovering even if forestry is highly intensive, and vice versa, lakes where even the BUS scenario will lead to re-acidification in the longer term. The proportion of the 2,631 lakes modelled in the year 2030 that will experience an annual net increase in calcium reserves in the soil, and thus a recovery of base saturation, falls from 30 per cent for the BUS scenario to 26 per cent for the MBR scenario. For the HBR scenario this figure drops further to 18 per cent. The percentage of lakes where forestry will lead to a net loss of calcium from the soil increases from 62 per cent for BUS to 68 per cent for MBR, and 78 per cent for HBR. At the same time the percentage of lakes where the supply and removal of calcium are almost in balance (annual difference within ±1 meqCa/m^2/year) falls from 8 per cent under BUS to 6 per cent and 4 per cent respectively under MBR and HBR. This can be compared with the situation in 2010, when 22 per cent of catchment areas had a net increase of Ca in the soil, 72 per cent had a net loss of Ca and 6 per cent were in balance (Figure 9).

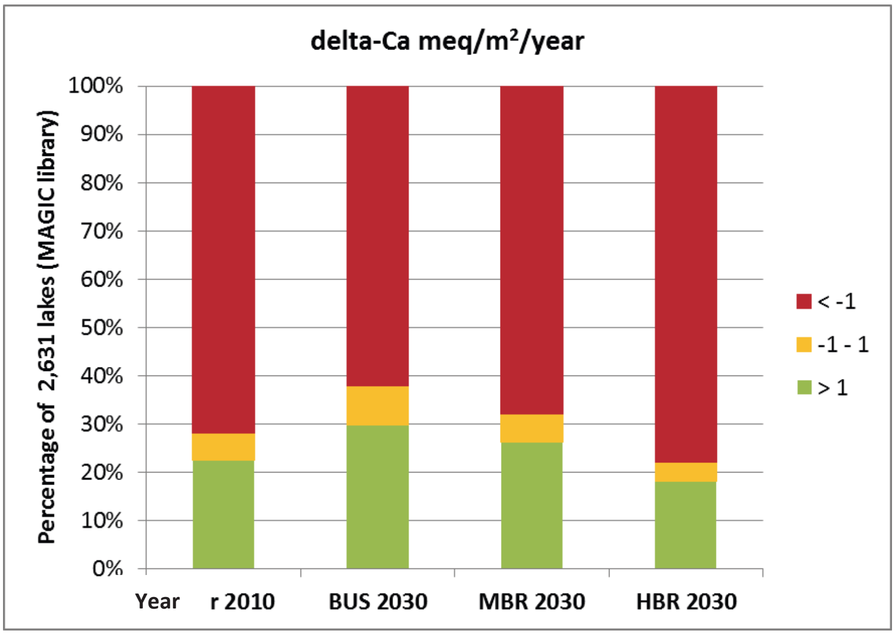


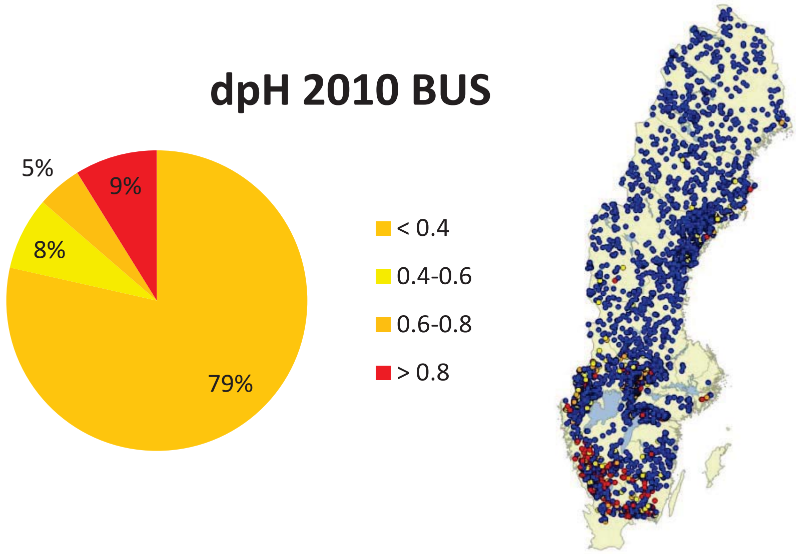
Figure 9. *Percentage of the 2,631 modelled lakes where calcium supply to the soil in the lake catchment areas (by atmospheric deposition and mineral weathering) exceeds (green) or falls short of (red) annual losses in the form of leaching and forest uptake, by more than 1 meqCa/m^2/year in 2010 and 2030 under three forestry scenarios. The catchment areas where supply and loss are in balance by ±1 meqCa/m^2/year are shown in orange. Based on HADLEY scenario for 2030.*

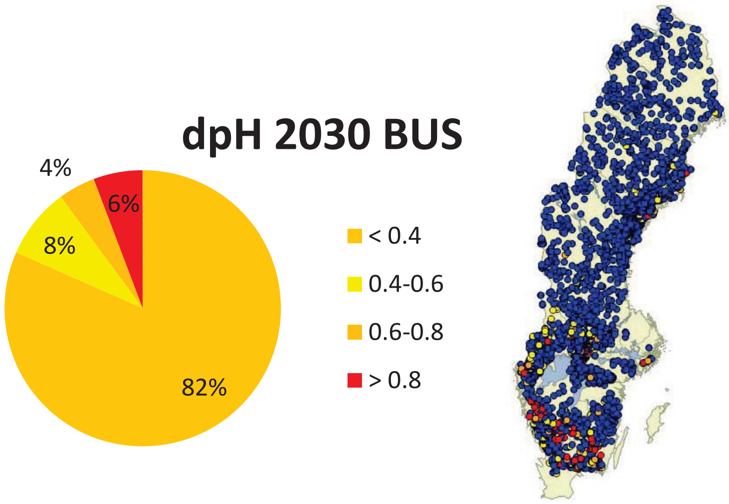
Lakes that are vulnerable to acidification are heavily over-represented among those modelled, so the picture is considerably less serious when looking at the total number of lakes in Sweden. For those lakes that are most vulnerable to acidification, however, the results indicate that unmodified forestry may lead to further weakening of already acidified systems that have poor chances of recovery.

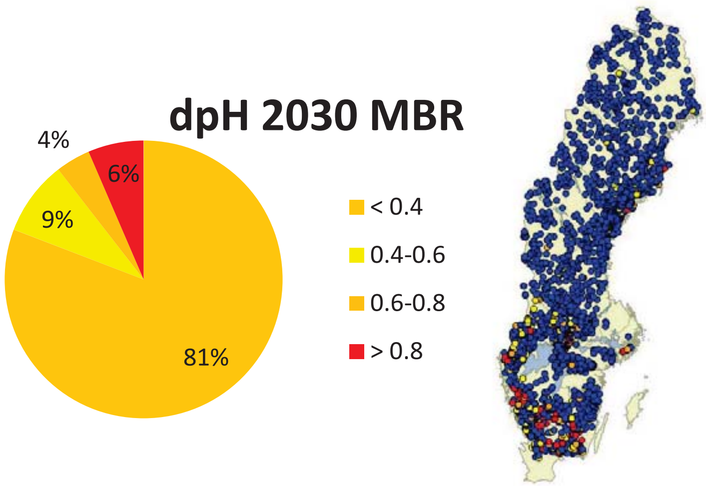
Future status of lakes

The problem of acidification centres on changes in base cation pools in soils in. The ANC of lake water is a good indicator of acidification status that can be measured and modelled. But the main problem of acidification is its impact on aquatic and terrestrial organisms. To describe the impacts on biota, pH is a more useful parameter than ANC. Lakes in Sweden are defined as acidified if the pH has fallen by at least 0.4 pH units between the year 1860 and the current year. The change in pH is calculated from the modelled ANC value.

A total of 2,631 lakes were modelled with MAGIC. These lakes are a selection of those affected by acidification in Sweden. It is therefore not possible to make a direct comparison with the estimates of acidified lakes given by the Swedish Environmental Protection Agency (2007), which used weighted values, so that each lake represented a certain percentage of the total number of lakes in Sweden. Of the 2,631 lakes that were modelled, the most acidified lakes (dpH>0.4) are located in southern Sweden. If forestry continues in a business-as-usual scenario (BUS) there will be some additional recovery from acidification by the year 2030, see Figure 10. There are only small differences between BUS and MBR, which may be explained by the fact that MBR can sometimes lead to less harvesting than BUS (depending on the region and type of felling). This is because the MBR scenario not only entails more production (than today) but also stricter environmental requirements, which means that certain parameters may be lower with MBR than with BUS. HBR, which entails more intensive forestry, also shows recovery from acidification by the year 2030, but then leads to some re-acidification by the year 2100. The percentage of acidified lakes in 2100 is lower than today, however.


dpH 2010 BUS
5%
9%
8%
79%
< 0.4
0.4-0.6
0.6-0.8
> 0.8


dpH 2030 BUS
4%
6%
8%
82%
< 0.4
0.4-0.6
0.6-0.8
> 0.8


dpH 2030 MBR
4%
6%
9%
81%
< 0.4
0.4-0.6
0.6-0.8
> 0.8

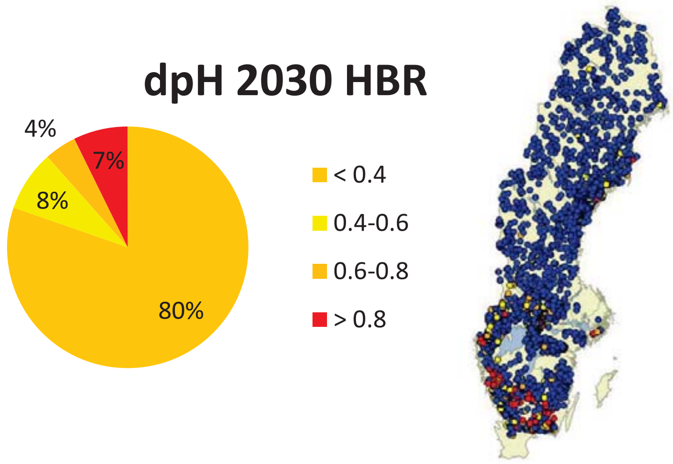


Figure 10. *Percentage of the modelled 2,631 lakes that are acidified (dpH>0.4) today (2010), or which will become acidified by 2030 under the three forestry scenarios. Most acidified lakes are in southern Sweden, but there are also problems with acidification in coastal areas of northern Sweden.*

Differences in the recovery process are more apparent when we look at a selection of lakes that are most vulnerable to acidification. Of the modelled 2,631 lakes, 783 (30%) had a pH value above 6.7 in 2010. These can be considered as relatively unthreatened by acidification, either because they have never been acidified or because they have already recovered. The average for the remaining 1,848 lakes fell from a pH of 6.26 in the mid-1900s to the lowest average value (pH 5.54) in the mid-1980s. In the period up to 2010 there has been some recovery, with the average pH rising to 5.82. However, this level is still more than 0.4 pH units lower than the preindustrial value. If the average value rises sufficiently to pass the dpH threshold of 0.4, the three modelled scenarios will have different outcomes. Under the HBR scenario, recovery will flatten out below the dpH 0.4 level; under MBR it will reach dpH 0.4 then flatten out; and under BUS the average value will no longer exceed the acidification criterion, dpH<0.4 (Fig. 11).

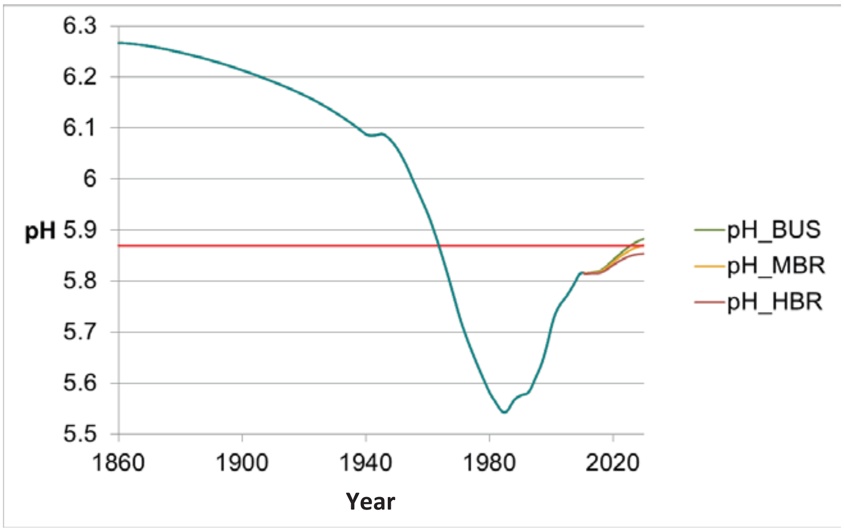


***Figure 11**. Average pH of lake water over time, under actual forestry and air pollution conditions from 1860 to 2010, and for the three forestry scenarios (BUS, MBR and HBR) from 2011 to 2030. The red horizontal line indicates dpH=0.4 below the pre-industrial level (1860). This figure does not include lakes with the highest pH (pH_{2010}>6.7, i.e. about 30% of the modelled 2,631 lakes).*

Influence of DOC on acidification

Leaching of dissolved organic carbon (DOC) affects the pH and ANC of water. According to the modelling results from FLUXMASTER the level of DOC in stream water will rise slightly between 2010 and 2030. On average, the increase will be 0.1 mg/l under ECHAM and 0.26 mg/l under HADLEY, i.e. a few per cent of the normal DOC levels of between 5 and 10 mg/l. This is not taken into account in the MAGIC results for ANC, since the model assumes a constant DOC over time, as the effect was considered negligible (a maximum change of 0.003 pH units).

Weathering in a changing climate

Increased weathering as a result of higher temperatures has been proposed as a process that could "compensate" to a certain extent for increased base cation loss due to harvesting branches and tops. Mass balance calculations were carried out in CLEO to examine this. The indirect effects on weathering and increased harvesting due to changes in growth and decomposition were not however examined in the study, nor were changes in humidity. The increase in weathering up to 2050 under the two climate projections (ECHAM and HADLEY) was calculated using the PROFILE model and compared with the increase in base cation losses if biomass removal is intensified from stems to stems and branches and tops. The results show that increased weathering does not compensate for the losses of removing branches and tops, except for a limited area in northernmost Sweden. In southern Sweden the base cation losses from harvesting branches and tops are considerably greater than the increase in weathering. This means that increased weathering due to rising temperature cannot generally be expected to compensate for base cation losses from harvesting branches and tops.

Eutrophication and leaching of nitrogen

Leaching of nitrogen from forest soil is a small part of the total load on surface water, but with climate change and more intensive forestry there is a risk that this leaching will increase and have a greater impact on the eutrophication status of lakes, rivers and coastal areas.

Future leaching was examined in CLEO with the aid of several models. The models describe the complex processes that control nitrogen turnover in soil and water, including uptake and release by micro-organisms and vegetation. The complex turnover of nitrogen in the ecosystem is difficult to describe with models and it is uncertain how the individual processes are affected by climate change. Small changes in assumptions about uptake and turnover can therefore lead to large relative differences in calculated leaching. This means that the results depend on the assumptions that are made in the models, so the results from several models (CoupModel, S-HYPE and FLUXMASTER) are presented here.

Future leaching of nitrogen and carbon

An analysis of weather and climate impact on the chemistry of nine closely studied small Swedish forest areas has shown that the water chemistry of small streams is not especially sensitive to temperature changes, but is sensitive to changes in water flow. The combined effects of climate change, atmospheric deposition and forestry under a total of 18 scenarios covering the entire country at high spatial resolution were simulated using the CoupModel, S-HYPE and FLUX MASTER models. The results indicate a moderate increase in DOC levels (around 2–7%, based on two models) under the BUS scenario, but decreasing levels under the MBR and HBR scenarios (one model). The results from CoupModel are summarised in Figure 12. In the case of transport to the sea, retention in lakes and waterways was a significant factor for nitrogen, but less significant for DOC.

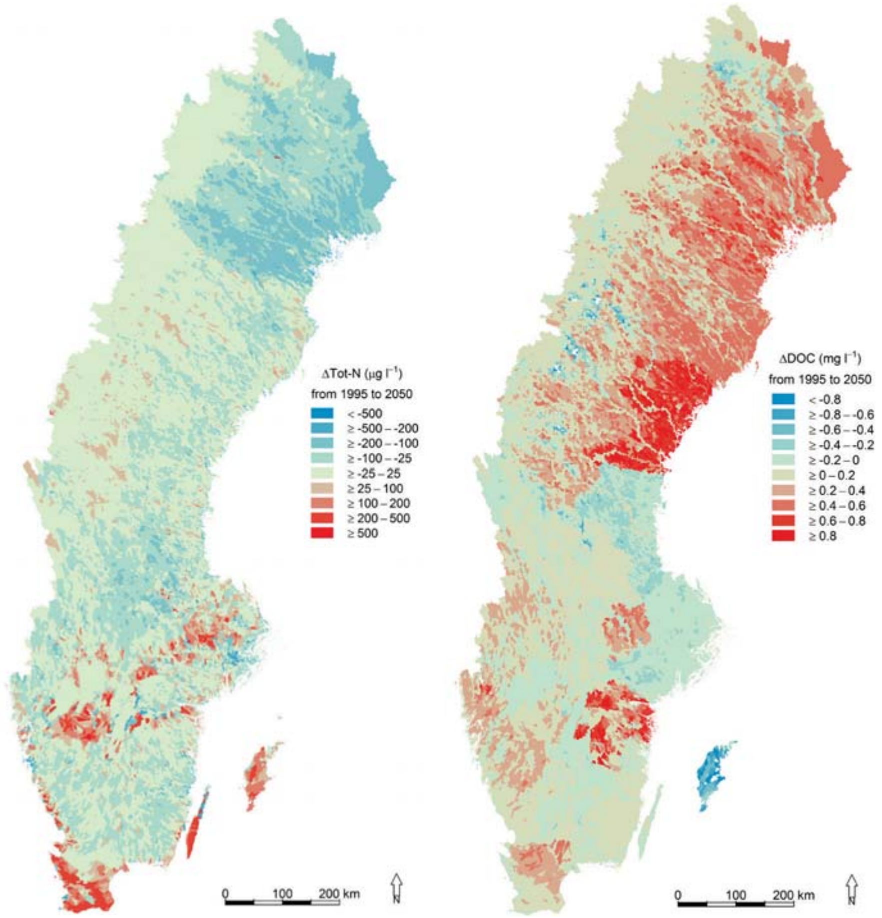


Figure 12. *Simulated changes in Total N (µg/l, left) and DOC (mg/l, right) after upscaling simulation results from CoupModel with NET. This scenario refers to ECHAM BUS 2050 compared with 1995.*

Figure 12 shows simulated changes in Total N and DOC after upscaling the results from CoupModel using the NET upscaling tool, for the scenario ECHAM BUS 2050 compared with 1995. Total N levels decrease in simulations modelled with CoupModel and ECHAM for the period up to 2050. The ECHAM scenario entails higher temperature, which means increased forest growth and plant uptake, while reduced nitrogen deposition under this scenario leads to a reduction in Total N levels. Based on county-by-county calculations using CoupModel, nitrogen levels in forest run-off under the BUS forestry scenario showed an average change of -12% (standard deviation = 12%), while the corresponding value for carbon is +5% (8%). According to ECHAM BUS, levels of DOC increased until 2050 in the northern parts of Sweden where the temperature rise was highest. This increase is explained by accelerated breakdown of organic matter and a slight increase in production of forest litter. The calculated changes were relatively moderate however.

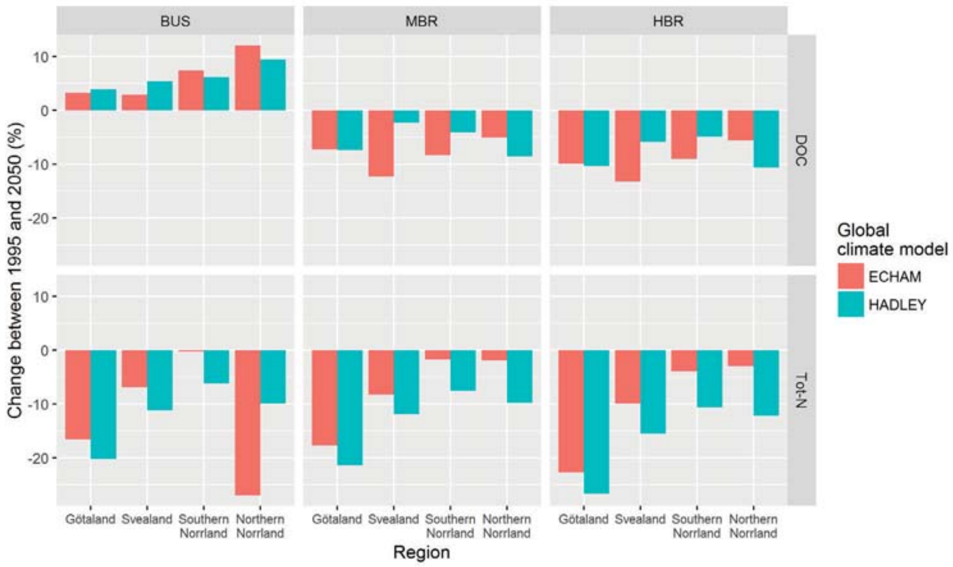


Figure 13. *Changes in the levels of DOC and Total N, simulated with CoupModel for ECHAM and HADLEY climate scenarios and BUS, MBR and HBR forestry scenarios.*

The results from CoupModel for the ECHAM and HADLEY climate scenarios and all three forestry scenarios – BUS, MBR and HBR – are summarised in Fig. 13. The results indicate a moderate increase in DOC levels (about 2–7%; S-HYPE also gave similar results) under the BUS scenario, but falling levels under MBR and HBR. In the case of transport to the sea, retention in lakes and rivers was a significant factor for nitrogen, but less significant for DOC.

S-HYPE simulations showed, on average, an increase in nitrogen levels with rising temperature. According to the results from the model, this increase exceeds the reduction in atmospheric deposition set in these scenarios, and the increase in denitrification that also occurs with rising temperature. However, the HYPE model does not include any feedback mechanism to reflect increased forest growth with improved access to nutrients, which may mean that the simulated increase in nitrogen leaching is slightly overestimated. A further uncertainty in the scenario simulations is the description of long-term changes in soil nitrogen reserves.

Although the process descriptions in CoupModel and HYPE have similarities, there are still differences between them (e.g. the feedback link to forest growth), and the rates of the individual processes may differ between model configurations. The use of multiple models may offer benefits as a way of highlighting the uncertainties in results, and clarifying which processes affect the estimated leaching rate. In summary, the results from the models point in different directions, but the changes in nitrogen transport were relatively moderate.

The role of agriculture compared to leaching from forests

The nitrogen content of run-off from agricultural soils is generally considerably higher than from forest soils. Because the focus of CLEO was forest soils, changes in nitrogen leaching from other types of land were modelled using the S-HYPE model. The results for agricultural soils were less clear in relative terms, showing both decreases and increases in modelled nitrogen leaching.

How big a problem could nitrogen leaching become in the future?

In the combined scenarios, changes in quantified levels and substance transport were relatively small up to the year 2050, especially in relation to uncertainties in the models and input data, and in relation to natural variations. Somewhat contradictory results were obtained for nitrogen concentrations in the run-off from forests, since the levels fell slightly under climate scenarios based on one model, but rose according to another model. In the case of leaching into the sea the changes were relatively small. The effect of temperature rise is small but increased precipitation in the future is expected to have a slightly greater effect.

Nitrogen deposition has not declined as much as sulphur deposition, and southern Sweden still receives considerably larger quantities of nitrogen from the atmosphere compared to the pre-industrial level. Overall, however, the results indicate that climate change and changes in forestry will not have any major effect on the leaching of nitrogen.

Eutrophication and acidification are serious threats to the Baltic Sea, and many different pollution sources contribute to this in addition to leaching from forest soils. Strategies for action and management therefore need to take into account a number of factors, including climate change, to ensure a healthy environmental status in the future (Jutterström et al. 2014).

Relative importance of three drivers: climate change, forestry and air pollution

A comparison of the relative impacts of future climate change, forestry and air pollution indicates that in many cases the share of environmental impact due to air pollution is declining relative to that caused by climate change and forestry. This is to be expected in view of the continuing reductions in emissions (and hence deposition) outlined in future scenarios. We must however keep in mind that this is relative impact, and for the system as a whole we must also take into account also those factors that have less impact. The remaining levels of sulphur and nitrogen deposition continue to affect ecosystems, and further emission reductions beyond those already accounted for in the CLEO calculations would favour recovery from acidification and reduce the risk of future eutrophication problems.

Acidification

According to our results, more intensive forestry has the potential in the worst case to cause re-acidification and increased leaching from forest soils. Increased weathering due to rising temperatures caused by climate change may counteract this to some extent, but the potential increase in weathering is generally considerably less than the increased base cation losses caused by more intensive forestry. Sulphur deposition will continue to have an acidifying effect on soil and water, even if its extent is greatly reduced thanks to the observed and predicted reduction in deposition levels. Base cation losses due to felling will therefore become relatively more significant, especially if forestry is intensified.

Nitrogen leaching

In the case of nitrogen leaching, forestry and deposition both have less impact than climate change, such as changes in precipitation and temperature. The climate is also the dominant factor when it comes to changes in future leaching of DOC. The expected changes in DOC (and DON) levels are relatively small in the short term (10–15 years).

The combined scenario calculations are based on realistic combined future changes in climate, deposition rates and forestry. But combined scenarios in which several factors change simultaneously do not allow us to evaluate the impacts of climate, forestry and air pollution individually. In order to isolate/estimate the importance of the individual impact factors, a sensitivity analysis based on the S-HYPE model was conducted for the whole of Sweden. The sensitivity analysis is based on an S-HYPE reference run using measured climate data for the period 1999 to 2008, and is not therefore linked to the input data for the climate scenarios. The purpose is to show the sensitivity of the model to changes in factors that are also included in the combined CLEO forestry and climate scenarios, and thus identify the dominant factors.

The results of the sensitivity analysis are shown in Figure 14, and indicate that changes in the climate may have greater impact on nitrogen leaching than changes in deposition and forestry.

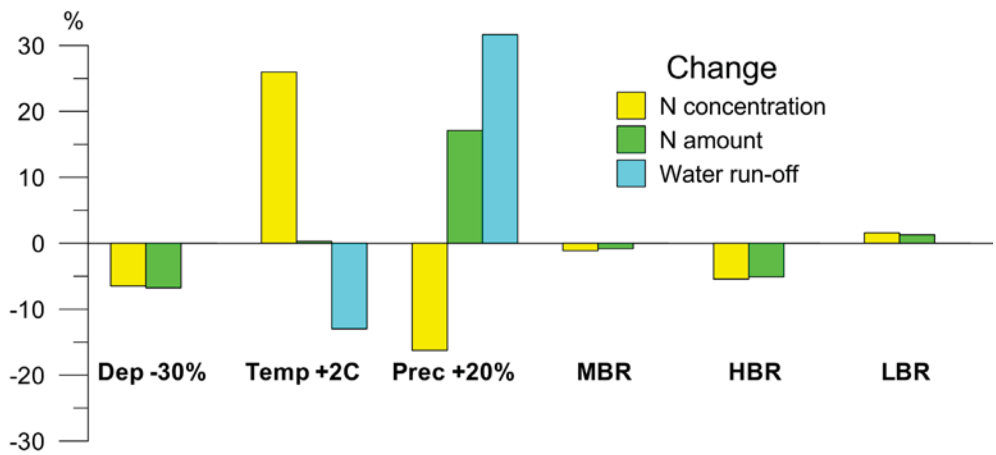


Figure 14. *Results of sensitivity analysis, with each factor varied independently. Changes in long-term average nitrogen concentration and amount transported to the sea from Sweden as a whole, according to simulations with S-HYPE, expressed in per cent from the reference simulation (1999–2008).*

The nitrogen content of run-off rose with increasing temperature but Total N transported to the sea was almost unchanged. Changes in precipitation had a relatively large effect on concentrations and transport for Sweden as a whole, while the forestry scenarios had a minor effect on calculated future leaching, as did the expected reduction in atmospheric deposition. An additional low biomass removal scenario (LBR) was constructed for the sensitivity analysis that entails a 30 per cent reduction in the removal of forest residue from forest soils. The relatively small responses to changes in forestry practice are due to the fact that a large proportion of the nitrogen that reaches the sea comes from sources other than the forest, and forest nitrogen reserves are so large that they have a low turnover rate. Intensive forestry (HBR scenario) may lead to reduced nitrogen leaching on roughly the same scale as the continuing decline in nitrogen deposition. The two less intensive forestry scenarios lead to a relatively small reduction (MBR) or increase (LBR) in nitrogen leaching.

Extreme events are increasingly significant when evaluating the Environmental Objectives

As sulphur deposition decreases, extreme events and disturbances have a growing relative impact on the status of soil-water and surface water. Storms that carry large quantities of sea salt and deposit it over forests have severe but temporary effects on soil-water. Disturbances in the form of storms or insect attack that have an adverse effect on the health of forests can cause significantly elevated levels of nitrate-nitrogen in soil-water. Nitrification also leads to increased acidification. The impact on soil-water may also lead to effects on surface water. Since the concentration of sulphate ions is lower today, chloride and nitrate anions play a greater role in transport between soil and water.

Acid episodes during sea salt episodes

Although sea salt is neutral, it is important to consider when monitoring the Environmental Objective of *Natural Acidification Only*. The reason is that sodium replaces other positive ions in soil particles such as hydrogen ions in acidic soils, which lowers the pH of the soil-water and potentially also surface water. There are documented episodes of heavy sea salt deposition in Sweden and Norway in the early 1990s that also involved the death of fish. These episodes are also apparent in soil-water chemistry measurements from the Throughfall Measurement Network (Krondroppsnätet), which show elevated levels of chloride and sodium during this period. In many cases, effects are also observed on acidification parameters such as pH, acid neutralising ability (ANC) and/or inorganic aluminium content. One example of changes in chloride content and pH is shown in Fig. 15.

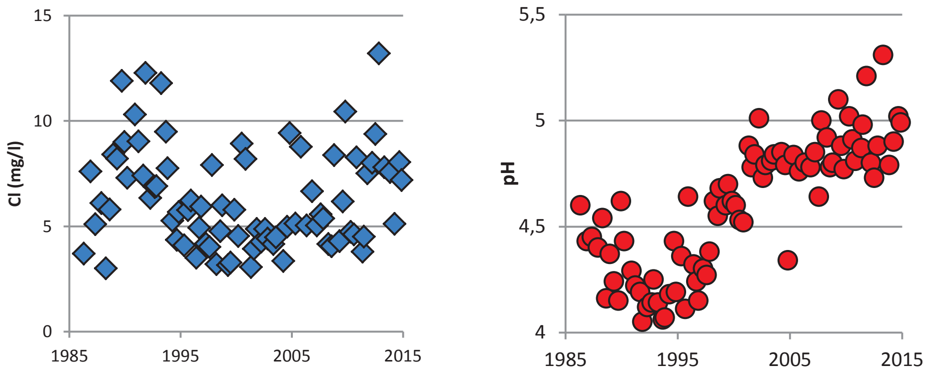


Figure 15. *Chloride content (Cl), and pH of soil-water in Hjärtsjömåla in Blekinge. The elevated chloride levels in the early 1990s are reflected in a temporary drop in pH. In addition to the sea salt period the pH curve also reveals some ongoing recovery from acidification.*

Nitrogen leaching after disturbances

Healthy, growing forest in Sweden takes up the largest proportion of inorganic nitrogen from the soil. The exception is in the far south-west of Sweden, where elevated nitrate-nitrogen levels in soil-water are common today. Disturbances that have an adverse effect on uptake by trees mean that elevated nitrate levels often also occur elsewhere in Sweden. This effect is often most pronounced in nitrogen-rich south-western regions. It has long been known that felling leads to considerably elevated nitrate-nitrogen levels in soil-water, accompanied by the risk of leaching into surface water. In Kallgårdsmåla in Blekinge and in Västra Torup in Skåne the observed concentration of nitrate-nitrogen rose to 20–25 mg/l after felling.

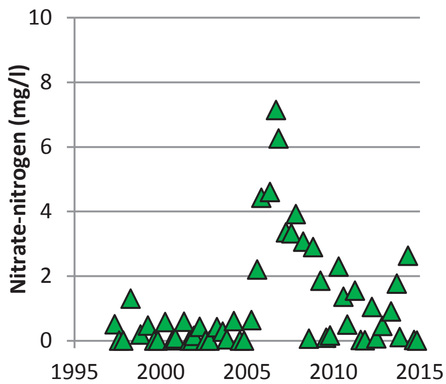


Figure 16. *Storm damage in Timrilt, Halland, after hurricane Gudrun in January 2005 (left) and the observed concentration of nitrate-nitrogen in soil-water in Timrilt (right).*

After hurricane Gudrun, in 2005, many monitoring sites within the Crown Drip Measurement Network also showed significantly elevated levels of nitrate-nitrogen, including Timrilt in Halland, see Figure 16. Insect attack is another disturbance that can affect soil-water chemistry. In Klippan, in the county of Västra Götaland, stands were attacked by spruce bark beetles in 2008, which killed all the spruce trees. This led to a sharp rise in nitrate-nitrogen in the soil-water for several years.

Growing significance of disturbances in the future?

It is unclear if and how the frequency of sea salt episodes will change in the future. It is however clear that their relative significance has increased now that sulphur deposition has declined. In many areas chloride ions have the greatest potential to transport hydrogen ions from the soil to surface water, and thus play a key role in the link between soil and water.

The frequency of storm damage and insect damage may increase as the climate becomes warmer and more humid. This may lead to increased nitrification, which in turn leads to increased acidification and greater leaching of nitrate-nitrogen, especially in areas where high levels of nitrogen have accumulated in the soil. This can also have an impact on surface water, especially if large areas are affected at the same time.

Leaching of mercury

As in the case of sulphur, emissions and deposition of mercury have fallen sharply over recent decades. Despite this there has not been an equally clear recovery, and the concentration of mercury in fish from a large number of Swedish lakes is above the limits set for human consumption. Part of the reason is that large quantities of mercury (from both anthropogenic and natural sources) have built up over a long time in forest soils and act as a source for leaching into surface water. Under normal conditions this leaching is relatively slow, but can be affected by forestry and soil disruption such as damage by vehicles.

To estimate the extent of forestry impact a national mercury database has been compiled for 166 forestry areas by examining completed projects that measured levels of total mercury and methyl mercury in run-off water. The database was then used to scale up leaching data for total mercury and methyl mercury to the national level, based on the current situation and alternative forestry scenarios. The upscaling study shows that, across Sweden, leaching of total mercury may rise by up to three per cent, while methyl mercury may rise by to six per cent as a result of more intensive forestry. At present, levels of total and methyl mercury are generally highest in south-west Sweden. Comparable results have also been presented in an experimental study (Eklöf et al. 2015b).

More intensive forestry and climate change may lead to more disturbances of forests in the future, such as damage by vehicles and by storms, which both affect mercury leaching. For example, more frequent use of heavy vehicles, as consequence of more forest fuel harvesting, ash recycling and fertilisation, combined with warmer and more humid winters, will increase the risk of damage by vehicles in parts of Sweden. Ground disturbance does not always lead to increased levels of methyl mercury, but observations show a statistical association. No scenario was modelled for the damage above, but a scenario was used for ditch clearing. Scaling up showed that the impact of this measure was extremely marginal for the country as a whole. Clearing of ditches can however have significant local effects. It is likely that disturbances such as damage by vehicles, storm damage and bark beetle attack would also have marginal effects on the leaching of mercury from a national perspective, but could have greater impact at local level.

Climate change can also affect mercury leaching, since increased precipitation results in more run-off. An experimental study by Munthe et al. (2016) shows that levels of total mercury and especially methyl mercury in surface water may rise in regions where precipitation is increasing.

Elevated mercury levels in surface water due to climate change and more intensive forestry in the future may also have a negative effect on fish stocks. An experimental study by Wu (2015) showed that the mercury content in fish rose by about 15 per cent in lakes in the catchment areas around felling sites, compared to the level before felling.

One limitation of the compiled mercury database is that the 166 measurement locations were not chosen to support generalisation of results to national level, but to suit the objectives of the individual studies. Among other things the timing of the measurements and the number of observations per measurement site vary between the projects, which contributes to uncertainties in the upscaling study.

In summary, it can be said that climate change and changes in future forestry may lead to higher mercury levels in surface water and freshwater fish, and thus lead to a risk of conflict with the environmental objective of *A Non-Toxic Environment*.

The forest and ecosystem services

Under CLEO, the main emphasis of efforts in ecosystem services was to clarify the concept, identify and describe the most important ecosystem services in Swedish forests, and conduct a quantitative analysis of the most important ecosystem services in the forest (Hansen et al. 2014; Hansen and Malmaeus 2015). A summary of the state of knowledge on economic valuation of ecosystem services was also produced, based on Swedish and Nordic studies. This element also included a discussion of future needs for research to supplement and/or improve an economic valuation of ecosystem services in forests (Takie and Hansen, 2014). A qualitative analysis of the links between various ecosystem services and acidification and eutrophication is presented here (Hansen, 2015).

How do acidification and eutrophication affect ecosystem services?

Air pollution affects forest ecosystems by modifying a range of common functions such as primary production (tree growth) and biogeochemical cycles. Acidification (N and S) and eutrophication (N) are the main processes linked to excessive deposition of N and S, and they in turn affect a wide range of ecosystem services that we depend on or utilise for our survival and welfare. These can be described and possibly valued systematically by using a framework for ecosystem services (MEA 2005; TEEB 2010). Table 3 classifies the main ecosystem services in Swedish forests in four categories – provisioning, supporting, regulating and cultural ecosystem services – and shows how they are linked to acidification and eutrophication.

Impact on provisioning ecosystem services

Growth in Swedish forests is limited by the availability of nutrients, mainly nitrogen. The deposition of nitrogen leads primarily to increased tree growth in nitrogen-limited ecosystems, as clearly demonstrated by experiments in forest soil fertilisation, where a clear growth response is seen for spruce on poor and moderate soils. The relative response is greater in northern Sweden than southern Sweden. The effects on growth enhance timber production and the supply of biomass for generating bioenergy. On the other hand, further nitrogen deposition below the nitrogen saturation level can lead to greater tree mortality.

Acidification of reindeer grazing land can reduce their food supply (lichens that are sensitive to acidification), but this effect is likely to be limited since reindeer generally live in parts of Sweden where acidification is not as pronounced. Some acidification-sensitive fungi react to increased nitrogen deposition, such as chanterelles, which have been shown to grow less well in acidified conditions, while other fungi appear to benefit, such as funnel chanterelles. In southern Sweden, increased nitrogen deposition and acidification, combined with denser forests that reduce daylight penetration, have probably contributed to reduced lingonberry crops, since the area of productive lingonberry soils has been drastically reduced. Blueberry yields from Swedish forest soils are also feared to have reduced as a result of nitrogen deposition.

The deposition of acidifying substances causes run-off water from forest soils to be acidic and rich in aluminium. This can harm aquatic plants and animals. Snails, molluscs and crustaceans are particularly sensitive groups of benthic animals. Many species of fish are also sensitive to acidification, such as roach and salmonids. The availability of fish has effects on recreational fishing (cultural ecosystem services).

As long as the soil retains its ability to buffer acidifying substances and there is adequate weathering, groundwater will be protected. In areas where this is not the case, groundwater loses its ability to neutralise the supply of acid, which leads to a decline in the quality of surface water and groundwater, and a rise in the content of harmful metals. Acidic groundwater that is used as drinking water will corrode household supply pipes, which raises the concentrations of metals (copper, cadmium and zinc) in the water.

Table 3. *The main ecosystem services in Swedish forests grouped into four categories – provisioning, supporting, regulating and cultural ecosystem services – and how they are linked to acidification and eutrophication. (+) indicates that acidification/eutrophication has a positive effect, while (-) indicates that acidification/eutrophication has a negative effect.*

Type	Ecosystem service	Impact of air pollutants: positive (+) and negative (-)
Provisioning services	Timber, pulpwood and biofuel	N deposition can enhance tree growth (+)
	Game	How game is affected by acidification and eutrophication, for example the uptake of heavy metals in the food chain, has not been established (?)
	Grazing animals and feed	Reindeer lichen are sensitive to acidification, but impact is small in relevant areas
	Berries	N deposition in southern Sweden contributes to smaller berry crops (-)
	Fungi	Fungi are affected by N deposition (and acidification); some species benefit, others are adversely affected (+/-)
	Clean drinking water	Acidification and nitrogen leaching can adversely affect the quality of surface water and groundwater (-)
	Recreational fishing in forest lakes	Many species of fish are sensitive to acidification, for example roach and salmonids; mercury leaching can make the fish unfit for consumption (-)
Supporting services	Biogeochemical cycles	A number of important processes are disrupted by elevated N deposition, such as decomposition, mineralisation, weathering and C sequestration
	Soil fertility	Acidification leads to leaching of base cations, which in turn can reduce soil fertility (-)
	Photosynthesis – primary production	N deposition can lead to increased growth, increased productivity (+)
	Natural habitats	Forest habitats are changing as a result of changes in species composition and a reduction in the number of species.
	Biodiversity and genetic resources	Some species are sensitive to acidification, while others are affected indirectly by changes in the availability of food; N deposition favours nitrogen-loving species (-)
Regulating services	Climate control, carbon assimilation and carbon sequestration	N deposition can lead to increased growth and increased carbon sequestration

	Prevention of storm damage	Increased N deposition can affect the ratio of root/tree biomass and weaken the root system (-)
	Natural control of pests and disease	Stands that are vulnerable as a result of acidification are at greater risk of pest attack (-)
	Clean oxygen-rich air	Vegetation filters out particles, absorbs gas from the air and thus cleans the air (+)
Cultural services	Recreation and fitness activities	Eutrophication affects recreational fishing. The species composition shifts towards more nitrophilic species such as algal blooms (-)
	Tourism	Eutrophication, acidification and mercury (see above) can affect fishing and outdoor tourism (-)
	Mental and physical health	Elevated heavy metal concentrations in game, mercury in fish (-)
	Environment and aesthetics	N deposition affects the flowering of wild species, and may enhance, impair and/or delay flowering depending on the species (-)

Impact on supporting ecosystem services

Soil fertility is reduced by leaching out essential base cations from the soil and by slowing down the decomposition of organic matter at lower pH values, and hence also reducing the mineralisation of nitrogen in the soil. Excessive nitrogen levels can lead to leaching of nitrates if more nitrogen is available than can be assimilated by plants. Soil acidification also leads to increased weathering. Since increased nitrogen deposition normally leads to increased growth, more carbon is bound up by photosynthesis and is incorporated in biomass and eventually in soil carbon. Topsoil is formed by the accumulation of organic matter (with increased nitrogen deposition) and by weathering. This can make the forest more sensitive to climate impact, disease and insect attack. Mycorrhizal fungi cannot tolerate low pH, and high nitrogen deposition leads to reduced growth and changes in species composition. Nevertheless, mycorrhizal fungi can protect plant roots from toxic levels of aluminium that can occur at low soil pH values, and by increasing the weathering of base cations.

Plants and soil-dwelling animals are generally adapted to a specific soil acidity. The sensitivity of individual species to air pollution and acidification varies. Some species are sensitive to acidification, so acidification may lead to the disappearance of these species. The most sensitive groups include fish, lichens, mosses, some fungi and small aquatic animals that are also directly affected by the low pH values of precipitation. Other species are indirectly affected as a result of changes in the availability of food or its complete disappearance. Yet other species that are nitrophilic may take their place and become dominant. Forest habitats will thus change as a result of changes in the composition and a reduction in the number of species.

Impact on regulatory ecosystem services

Studies indicate that nitrogen deposition will lead to increased carbon sequestration in tree biomass in nitrogen-limited forests. This increase in growth may also lead to greater leaf/needle biomass and slower decomposition, which will lead to increased carbon storage in the soil.

The effect of nitrogen deposition on growth affects how much water can be extracted, and hence the availability of fresh water. The availability of water again affects the ratio of root/tree biomass, which may weaken the root system relative to the size of trees, and make trees vulnerable to storm damage. Stands that have become vulnerable as a result of acidification are also at greater risk of attack by pests.

Impact on cultural ecosystem services

Increased deposition of nitrogen may favour the dominance of more nitrophilic species such as nettles and algal blooms in downstream lakes, which can reduce the aesthetic value as well as opportunities for recreation and fitness activities. Eutrophication of waterways and lakes has implications for recreational fishing, since it affects food webs and fish stocks. It also has an impact on our desire to spend time in nature, which in turn has implications for human health. Nitrogen deposition affects the flowering of wild species, and may enhance, impair and/or delay flowering, depending on the species. Flowering is an important element in our perception of wild habitats and the aesthetic value of nature.

Synergies and conflicts between environmental objectives and policies – forestry and emissions perspective

The general aim of CLEO is to clarify how climate change may affect the environmental status of the air, soil and water. In the same way that climate change can impact on several environmental issues simultaneously, changes in social activities, environmental policy and emission reduction measures can affect several environmental problems at the same time. One clear example of a social activity that has a big impact on the environment is the production of electricity and heat, which over the years has led to environmental problems such as acidification, eutrophication, global warming and mercury emissions. Since these activities affect the environment negatively in many ways, it is clear that regulation of such activity will also affect several environmental problems at the same time. Sweden has chosen to tackle environmental problems by setting up 16 individual Environmental Objectives and, as outlined above, efforts to achieve one objective sometimes also help us achieve other environmental objectives. But we must also ask ourselves: In what way? And how much? These questions are important in assessing our potential to achieve the Environmental Objectives and their cost to society.

Within CLEO we have tackled these policy issues under the umbrella term "synergies and conflicts". We have focused on the links between several environmental problems and environmental objectives, to identify synergies and conflicts in proposed action plans in environmental policy, in forestry policy and in that part of the environmental policy that deals with atmospheric emissions of sulphur, nitrogen, particles, volatile organic hydrocarbons and greenhouse gases.

Effects of forestry measures on environmental objectives – synergies and conflicts

Climate change affects forest ecosystems in many ways, through the direct consequences of changes in temperature and precipitation that are described in previous sections, through policy measures to reduce climate change, and through changes in the risks of forest damage that have also been addressed earlier. This section describes the effects on the Environmental Objectives of *Only Natural Acidification*, *Zero Eutrophication* and *A Non-Toxic Environment* of two policy measures – 1) increased forest fuel harvesting in the form of branches and tops (grot) and 2) fertilisation according to the needs of the stands (BAG) to enhance growth and hence forest fuel yield.

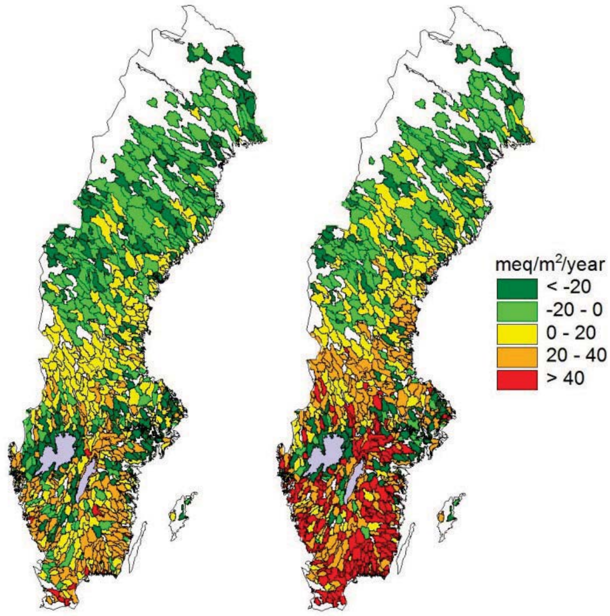
Effects of forest fuel harvesting on *Natural Acidification Only* and *Zero Eutrophication*

The removal of branches, tops and stumps means that significantly more nutrients are removed from the ecosystem than during the harvesting of stems alone. Removal of the base cations calcium, magnesium, potassium and sodium also means that a large proportion of the soil acidification caused by tree growth is made permanent. If we do not compensate for this nutrient loss, by recycling ash for example, increased extraction will be in conflict with the environmental objective of *Natural Acidification Only*.

Under CLEO and an associated project for the Swedish Environmental Protection Agency a “critical base cation removal” figure has been calculated. The calculation is based on the same concept as the “critical load for acidification”, i.e. the maximum permissible deposition of acidifying substances that will not lead to exceedance of a critical threshold, for a constant base cation uptake. The critical base cation removal is instead calculated as the maximum permissible base cation removal that will not lead to exceedance of a critical threshold if deposition is kept constant. In the latter case the critical threshold is an ANC value of zero for soil-water.

The calculations show that critical base cation removal is generally exceeded in southern Sweden and parts of central Sweden with stem removal alone, although exceedance is limited in many areas, see Figure 17. Harvesting of branches and tops in these areas would result in significantly higher exceedance. Harvesting of branches and tops would also lead to exceedance in a large proportion of forest soils in northern Sweden. Modelling with the dynamic MAGIC model (see previous section) gives results along the same lines, but shows that the short-term effects, up to 2020/2030, are expected to be small, especially in surface water.

The removal of nitrogen through the harvesting of branches and tops may favour the environmental objective of *Zero Eutrophication*, particularly in the most south-westerly parts of Sweden that have a large nitrogen surplus. A simulation based on the ForSAFE model, in Västra Torup in northern Skåne, shows significantly elevated nitrate-nitrogen levels in soil-water after felling in 2010, which was also observed in the field. The simulation also shows a lower nitrogen content if the branches and tops were harvested rather than the stems alone. The difference was even greater for harvesting during the current rotation period (Zanchi et al. 2014).



a. b.

Figure 17. *Exceedance of critical base cation removal for harvesting of stems (a) and for harvesting stems + branches and tops (b). Positive values indicate exceedance while negative values indicate levels below critical base cation removal. Effects of climate change on weathering and growth were not taken into account in these calculations.*

Effects of BAG on *Natural Acidification Only* and *Zero Eutrophication*

Fertilisation according to the needs of the stands (BAG) has recently been discussed as a means of increasing growth, carbon sequestration and the potential for forest fuel harvesting. BAG was part of a proposal for a revision of the Swedish Forest Agency's recommendations, but was not incorporated in its recommendations. A review of current BAG trials was conducted for CLEO. The conclusion is that fertilisation according to the needs of the stands leads in some cases to very high levels of nitrogen leaching, while in other cases it does not result in any major change. In summary, we do not currently have an adequate understanding of how BAG should be implemented to minimise risks to the environmental objective of *Zero Eutrophication*. In an associated project, nitrogen leaching results from fertilisation according to the needs of the stands in southern Sweden were scaled up, based on existing trials. Figure 18 presents the results, which show significantly higher gross leaching of nitrogen when five per cent of forest soil was dressed with fertiliser following the BAG approach, compared with current fertilising practice. The number of trials conducted with BAG is small, however, so there is considerable uncertainty about its effects. The effects of BAG on *Natural Acidification Only* should theoretically be small, since it involves the addition of base cations as well as nitrogen. Excessive nitrification would however result in the release of hydrogen ions, which leads to increased acidification, so in practice this environmental objective may also be adversely affected.

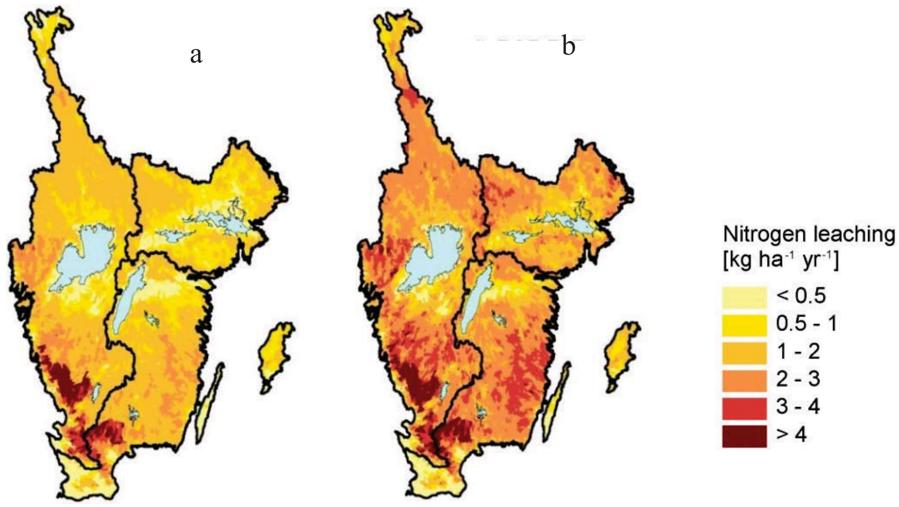


Figure 18. *Nitrogen leaching based on current fertilisation and felling practices (a), and with fertilisation according to the needs of the stands (BAG) on 5% of productive forest soil (B).*

Effects of increased forest machinery activity in the forest on the environmental objective of *A Non-Toxic Environment*

More intensive forestry, for example through fertilisation, and harvesting of branches and tops, also means more driving in the forest. This in turn may increase the risk of mercury leaching into surface water and thus have a negative impact on the environmental objective of *A Non-Toxic Environment*. The compilation of empirical data in CLEO has led to the conclusion that mercury levels are often but not always higher after disturbances. The causal link is not however completely clear yet. Scaling up this empirical data to the national level shows that the level of methyl mercury is highest in south-western Sweden, followed by south-east Sweden and western Svealand. A warmer and more humid climate in the future is expected to increase the risk of damage by vehicles and hence mercury leaching.

Synergies and conflicts between environmental objectives and policies

Combined impact of air pollutant emissions

Emissions of sulphur, nitrogen, particles, volatile hydrocarbons and greenhouse gases have multiple effects and therefore affect several different environmental objectives directly or indirectly. Table 4 below gives an overview of the emissions that were analysed during CLEO and their impact on four of Sweden's environmental objectives.

It is widely known that traditional air pollutants affect acidification, eutrophication and *Clean Air*. One aspect that has received growing attention in recent years is the influence of air pollution on the climate through the role of short-lived climate forcers/pollution (SLCF/SLCP). This was recognised some time ago but gained wider publicity when methane and soot particles were found to make a significant contribution to global warming, so reducing emissions would make it easier to achieve the climate target. One difficulty is that other particulate components such as sulphur and organic particles cool the climate, so reducing emissions of these leads to further warming. Because compounds with warming and cooling effects are often are emitted by the same source, careful analysis is needed to identify the most cost-effective solutions.

Table 4*. Emission sources, air pollutants and environmental impact that were analysed for synergies and conflicts in CLEO.*

Primary source of emissions	Airborne emissions/ Pollutant	Does it affect environmental objective?				Other environ-mental effects
		Natural Acidification Only	*Zero Eutrophicatio n*	*Clean Air*	*Limited Climate Impact*	
Combustion/ Processes	SO_2/SO_4^{2-}	Yes	Yes	Yes	Yes/SLCP	
Combustion	NO_x/NO_3^- (etc.)	Yes	Yes	Yes	Yes/SLCP	Ozone damage
Agriculture	NH_3/NH_4^+	Yes	Yes	Yes	Yes/SLCP	
Combustion/ Wear	Primary particles			Yes	Yes/SLCP	
Solvents (manufacturer/u ser)	NMVOCs			Yes	Yes/SLCP	Ozone damage
Agriculture/ Energy	CH_4			Yes*	Yes/SLCP	Ozone damage
Combustion	CO_2				Yes	Acidification of the sea

Combustion, i.e. for production of electricity and heat, or in engines for transport, is the dominant anthropogenic source of air pollution (see table above), and when it uses fossil fuel is also a key source of anthropogenic CO_2. Wide-reaching measures such as reducing the sulphur content of fuel or scrubbing sulphur from emissions have been very successful in cutting SO_2 emissions, which has had a very positive effect on acidification and health.

The presence of ground-level ozone is dependent on anthropogenic emissions of NO_2 and VOC. Ozone is estimated to have an atmospheric lifetime of around one month, which means that it can spread over the entire hemisphere. In recent times, long-distance transport between continents and rising levels of atmospheric methane have been put forward as the reason for increasing background levels of ozone.

Ozone is harmful to health; around 25,000 premature deaths occur in the EU each year due to high ozone levels (Amman et al. 2014). Ozone impairs the growth of crops and forests, and thus reduces food yields and forestry production. Reduced growth also means a reduction in the uptake of CO_2. Research in this area is ongoing, but it has been estimated that CO_2 uptake is reduced by up to 10 per cent, which is significant for the global carbon budget. Methane also has a key role in measures to reduce ozone levels, partly through its influence on ozone levels but also because it is a significant greenhouse gas. Anthropogenic methane is considered by the IPCC to contribute to warming equivalent to 1 W/m^2, after taking into account the ozone formed by methane (IPCC 2013). The current level of warming due to CO_2 is estimated at around 1.7 W/m^2.

It is clear that the interactions between air pollutants and greenhouse gases, their impact on ecosystems and their effects on the atmosphere must be taken into account when we develop action plans.

Advice on how to handle synergies and conflicts between environmental objectives and emission reduction measures

It is difficult to draw general conclusions about how Sweden can maximise synergies and minimise conflicts between measures to reduce emissions of greenhouse gas emissions and air pollutants, because we also need to allow for gaps in our knowledge and uncertainties in data. Based on the work done for CLEO and a synthesis of other studies, we present some general advice below, together with key aspects that should be incorporated when formulating courses of action for reducing emissions.

1. Air pollution must be reduced because of its massive impact, especially on health. Efforts to reduce the air pollution in Sweden should therefore be guided by their effect on air quality, acidification and eutrophication, not their effect on the climate. Greenhouse gas emissions should nevertheless also be taken into account when formulating plans of action. It should be noted however that:
    a. Changes in emissions of SO_2 in the EU since 1980 have had a significant but relatively limited warming effect on the climate of

the Arctic. Current emissions are relatively small and any further reductions in emissions of SO_2 within the EU will thus have marginal effect on the climate (Acosta et al. 2015).

  b. The potential to reduce emissions of short-lived climate pollutants (SLCP) in Sweden is fairly low in relation to their impact on the climate. SLCP abatement measures that are relatively easy to implement would at most cut Sweden's total forecast greenhouse gas emissions by 0.1–3.0 per cent by 2030 (Kindbom et al. 2015).

2. Climate effects should be considered when reducing emissions of air pollutants, by aiming to cut ozone levels, and by selecting those measures that give the lowest CO_2 emissions. Reducing emissions of methane, a greenhouse gas and ozone precursor, is probably the most important Swedish air pollution measure from the climate perspective. Reducing ozone levels also increases the uptake of CO_2 by ecosystems, which is key priority for the climate.
3. Energy efficiency measures and wind and solar power provide synergies.
   a. CLEO analyses show that national energy scenarios that focus on energy efficiency enable synergies between reducing emissions of air pollutants and greenhouse gases (Åström et al. 2013).
4. Reducing CO_2 emissions by using biofuels carries a risk of conflicts between climate targets and other environmental objectives
   a. Calculations (CLEO 2014) show that the Electricity Certificate System is a blunt instrument and has not taken into account effects on emissions of air pollutants. The economic cost of these air pollutant emissions matches or exceeds the value of the traded electricity certificates.
   b. The same report also reveals increased emissions of air pollutants due to greater domestic use of biofuels. Åström & Tohka et al. (2013) also show how national energy scenarios that focus on greater use of biomass in small-scale wood burning carry the risk of raising emissions of SLCP/SLCF so much that they counter air quality targets and climate targets.
   c. Increased burning of biomass for energy purposes can lead to higher emissions of air pollutants, especially particulates from small-scale wood burning. In many cases this can be countered by choosing modern technology, such as automatic pellet boilers (Gustafsson and Kindbom, 2014).

Outlook for environmental objectives and abatement measures

Environmental quality objectives in a changing climate – do we need a different approach for the future?

The main aim of the research carried out under CLEO was to study how climate change may influence environmental effects that are largely caused by the deposition of air pollutants. The relationship between deposition and effects becomes less obvious, however, when we take into account other influencing factors (such as forestry and the climate). Acidification, eutrophication and the damage to health and ecosystems caused by air pollutants and elevated mercury levels in fish are all well-known problems, for which the risks to ecosystems and human health have been documented for decades. Today, emissions of the air pollutants that cause these problems have been considerably reduced in most cases, but the effects are still present in varying degrees. Measures still need to be taken on the emissions front, in particular for nitrogen, and additional factors need to be considered, such as climate change and changes in forestry. The latter is partly a consequence of the former: increased use of forest biomass for energy and materials is an important part of national and regional strategies to reduce the use of fossil fuels and hence reduce impact on the climate.

The situation today is in many respects more complex and involves more factors that often interact in different ways, which makes it more difficult to forecast future effects and determine what measures are needed. CLEO has produced a number of clear results relating to ozone and recovery from acidification in a changing future climate. In the case of nitrogen leaching and eutrophication, the research has revealed a number of uncertainties. These are largely due to the fact that nitrogen in its different forms is an essential nutrient and is therefore assimilated and converted in different parts of ecosystems. Having an adequate understanding of the processes involved and how they are affected by changes in the climate is essential in order to make realistic forecasts. The results from CLEO show that this is not always the case, and we must satisfy ourselves with identifying the probable direction and magnitude of change.

This complexity means that future work on environmental objectives, impact assessments and abatement strategies should follow an integrated approach that allows us to evaluate several influencing factors simultaneously, to develop models in parallel with continued environmental monitoring and to incorporate results from field experiments. This will place greater demands on building up knowledge, models and research results, and on the way we set objectives and reach decisions based on information that does not always describe precise quantitative changes or effects.

The way we describe risks for future negative impact on ecosystems and health is one of these future challenges. Other challenges include how we communicate messages that are proportional to the scope of the problem, and how we contribute to public opinion and the political will to tackle problems that have been identified or are likely to affect us in the future.

Important questions for the future

The research from CLEO has given us new and relevant knowledge that is hopefully useful for developing future strategies for air pollution, the climate and forestry. The research has also given an insight into gaps in our knowledge, where continued research may shed further light on the issues covered by the programme, as well as related questions.

Emissions, dispersion and deposition of air pollutants

- Effects on atmospheric levels and deposition of ***global and hemispheric emission changes*** (primarily ozone and PM). This requires a better understanding of, for example, secondary formation of PM and ozone, and links to different emission sources.
- More knowledge about ***ammonia emissions*** is important for assessing the influence of ammonia on eutrophication, as well as its impact on the formation of secondary particles.
- Because the climatic effects and health effects of PM depend on the ***physical and chemical properties of the particles*** we need a better understanding and more accurate characterisation to facilitate linking of effects to emission sectors and abatement measures.
- ***Emissions of nitrogen*** are falling, but it is surprisingly difficult to show that deposition is decreasing: a better understanding of nitrogen deposition processes and turnover is needed.
- For the future, we need a better understanding of the ***long-term effects of climate change*** during extreme events (forest fires, heat waves) and changes in the growing season, vegetation, etc. How are air quality, ecosystems and water quality affected?

Better knowledge of the processes that control leaching from forest soils in the long term: carbon, nitrogen and mercury.

- There is a need for more knowledge about ***processes that control leaching from forest soils of carbon, nitrogen and mercury,*** to permit more reliable, long-term forecasts. This includes interactions between the soil and water, weathering and organic matter turnover. Experimental studies and long-term environmental monitoring are important for our understanding of processes and to enable monitoring of trends and the evaluation of models.

- The ***long-term impact of climate change and land use on soil carbon and nitrogen reserves*** require further study with regard to mineralisation, plant uptake and nitrogen turnover in different types of soil – as well as the ***impact of ground-level ozone***.

Abatement strategies, emission reductions

- Better data and tools for the analysing the ***cost-effectiveness of local and national measures*** in comparison with international treaties and agreements.
- Greater focus on ***action strategies for agricultural and industrial processes*** as important sectors in future abatement efforts. Emissions from these sectors depend on more complex and interrelated activities compared with the energy and transport sector, and appropriate analysis methods need to be refined and applied.
- Further development of methods for linked analysis of ***abatement strategies to reduce air pollutant emissions should always include analyses of greenhouse gas emissions***. The aim should be to maximise synergies between abatement measures for emissions of air pollutants and greenhouse gases.
- Basis for the development of ***abatement strategies for methane***. Better understanding of emissions, measures, effects and cost per instrument.

Forestry and biomass use

- Ongoing development of the use of Swedish forest resources for energy production and to provide raw material for a future bio-based economy will place greater demands on ***integrated assessment of the sustainability of various forestry scenarios***. The effects of forestry on carbon and nitrogen turnover and leaching into surface water, acidification and recovery, continue to be important environmental aspects that should be taken into account, together with biodiversity and the effects on various ecosystem services.
- Continued acquisition of knowledge on ***emissions from small-scale wood burning*** and how they are affected by boiler age and performance, frequency of use, etc., is one example of a key area where we need more knowledge about the use of biomass.

References

Acosta Navarro, J., Varna, V., Ekman, A., Riipinen, I., Seland, Ø., Kirkevåg, A., Struthers, H., Gauss, M., Iversen, T. and Hansson, HC. 2015. Amplification of Arctic warming by air pollution reductions in Europe, submitted to Nature Geoscience.

Amann, M., et al. (2014). The Final Policy Scenarios of the EU Clean Air Policy Package, TSAP report #11.

CLEO (2014). Klimatförändringen och miljömålen – Rapport till Naturvårdsverket inför Fördjupad Utvärdering 2015. J. Munthe.

Cosby, B.J., Ferrier, R.C., Jenkins, A. & Wright, R.F. 2001. Modelling effects of acid deposition: refinements, adjustments and inclusion of nitrogen dynamics in the MAGIC model. Hydrology and Earth System Sciences, 5, 499–517.

Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright. 1985. Modelling the effects of acid deposition: Assessment of a lumped parameter model of soil water and streamwater chemistry. Water Resources Research 21: 51–63.

Eklöf, K., Lidskog R., Bishop K. 2015b Managing Swedish Forestry's Impact on Mercury in Fish: Defining the impact and mitigation measures: Forestry's impact on mercury. Ambio, in press.

Eklöf, K., Kraus, A., Futter, M., Schelker, J., Meili, M., Boyer, E., Bishop, K. 2015a. A parsimonious model for simulating total mercury and methylmercury in boreal streams based on riparian flow paths and seasonality. Environ. Sci. Technol. DOI: 10.1021/acs.est.5b00852

Engardt, M. and Langner, J. 2013. Simulations of future sulphur and nitrogen deposition over Europe using meteorological data from three regional climate projections. Tellus B 65, 20348, http://dx.doi.org/10.3402/tellusb.v65i0.20348

Gustafsson, T. and Kindbom, K. (2014) Swedish air pollutant emission scenarios to 2050 – CLEO project report. IVL B2227

Hansen K., Pihl Karlsson G., Ferm M., Karlsson P.E., Bennet, C., Granat, L., von Brömssen, C., Kronnäs V., Engardt, M., Akselsson, C., Simpson, D., Hellsten S., Svensson, A. (2013). Trender i kvävenedfall över Sverige 1955–2011. IVL Rapport B2119, 76 pp.

Hansen K., Malmaeus M., Lindblad M. (2014). Ekosystemtjänster i svenska skogar. IVL Rapport B2190, 85 pp.

Hansen K., Malmaeus M. (2015). Ecosystem services in Swedish forests. Scandinavian Journal of Forest Research (In review).

Hansen, K. (2015). Luftföroreningars påverkan på ekosystemtjänster i svenska skogar. Intern CLEO-rapport.

Hytteborn, J. K., J. Temnerud, R. B. Alexander, E. W. Boyer, M. N. Futter, M. Froberg, J. Dahne and K. H. Bishop 2015. Patterns and predictability in the intra-annual organic carbon variability across the boreal and hemiboreal landscape. Science of the Total Environment 520: 260-269.

IPCC (2013). Technical Summary. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner et al. Cambridge, UK and New York, USA, Cambridge University Press.

Jansson, P.E. 2012. CoupModel: Model use, Calibration, and Validation. Transactions of the American Society of Agricultural and Biological Engineers. 55(4).pp.

Jansson, P.-E. and Karlberg, L., 2004. CoupModel: Coupled heat and mass transfer model for soil-plant-atmosphere systems. TRITA-LWR Report 3087. Stockholm, Sweden: Royal Institute of Technology, Department of Land and Water Resources Engineering.

Jutterström, S., Anderson, H.C, Omstedt, A., Malmaeus, J.M. (2014). Multiple stressors threatening the future of the Baltic Sea-Kattegat marine ecosystem: Implications for policy and management actions. Marine Poll. Bulletin, 86, 1–2, 468–480.

Kindbom, K., et al. (2015). Kortlivade klimatpåverkande luftföroreningar (SLCP) – Underlag för övervägande om etappmål, IVL-rapport C99. IVL.

Klingberg, J., Engardt, M., Karlsson, P.E., Langner, J. and Pleijel, H. 2014. Declining ozone exposure of European vegetation under climate change and reduced precursor emissions. Biogeosciences. 11, 5269–5283. doi:10.5194/bg-11-5269-2014

Langner, J., Engardt, M. and Andersson, C. 2012. European summer surface ozone 1990–2100. Atmos. Chem. Phys. 12, 10097□0105. doi:10.5194/acp-12-10097-2012

Lindström, G., Pers, C., Rosberg, J., Strömqvist, J. and Arheimer, B. 2010. Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. Hydrology Research 41.3–4, 295-319.

MEA: Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-being: Synthesis. World Resources Institute. Island Press, Washington, DC. 137 pp.

Moldan F., Cosby, B.J. and Wright, RF. 2013. Modeling Past and Future Acidification of Swedish Lakes. Ambio 42(5):577-86, ISSN 0044-7447, DOI 10.1007/s13280-012-0360-8

Munthe, J., Moldan, F. and Hult Mountain, H. Climate change and mobilisation of mercury in the forest soil – Effects of artificially increased precipitation on mercury and methyl mercury in runoff. I manuskriptform.

Naturvårdsverket 2007, *Bara Naturlig Försurning* Underlagsrapport till fördjupad utvärdering av miljömålsarbetet, NV Rapport 5766, 116p.

Schwarz, G.E., Hoos, A.B., Alexander, R.B. and Smith, R.A. 2006. The SPARROW surface water-quality model: Theory, application, and user documentation. U.S. Geological Survey Techniques and Methods Report, Book 6, Chapter B3, U.S. Geological Survey, Reston, 248 pp. http://pubs.usgs.gov/tm/2006/tm6b3/PDF.htm

Skogsstyrelsen, 2008. Långsiktiga konsekvenser av olika sätt att sköta och bruka den svenska skogen Skogliga konsekvensanalyser och virkesbalanser 2008, SKA-VB 08. http://www.skogsstyrelsen.se/Global/myndigheten/Projekt/Regeringsuppdrag/SKA-VB%2008%20Popul%C3%A4rversion.pdf

Strömqvist, J., Arheimer, B., Dahné, J., Donnelly, C. and Lindström, G. 2012. Water and nutrient predictions in ungauged basins: set-up and evaluation of a model at the national scale, Hydrological Sciences Journal, 57:2, 229-247.

Sverdrup, H and Warfvinge, P. 1993. Calculating field weathering rates using mechanistic geochemical model – PROFILE. Applied Geochemistry 8, 273–283.

TEEB (2009). TEEB climate issues update. September 2009. http://www.teebweb.org/

Tekie H., Hansen K. (2014). Ekonomisk värdering av ekosystemtjänster i skog. Intern CLEO rapport, Deliverable D4.3.3, 17 sidor.

Wallman, P., Svensson, M., Sverdrup, H., Belyazid, S., 2005. ForSAFE – an integrated process-oriented forest model for long-term sustainability assessments. Forest Ecology and Management 207, 19–36.

Winterdahl M., Temnerud, Futter, M., Löfgren, S., Moldan F., and Bishop, K. 2011. Riparian zone influence on stream water total organic carbon concentrations at the Swedish Integrated Monitoring sites. Ambio. 40(8): 920-930.

Wu, P., Martin, J., Åkerblom, S., von Brömssen, C., & Bishop, K. 2015, June. Forestry effects on mercury levels of European perch (Perca fluviatilis) in Swedish lakes. Poster session presented at: 12th International Conference on Mercury as Global Pollutant; Jeju, South Korea

Wu, P., Martin, J., Åkerblom, S., von Brömssen, C., & Bishop, K. In prep. Forest clearcutting effect on lake fish mercury – a pilot study of forestry practices in Swedish boreal lakes.

Zanchi, G., Belyazid, P., Akselsson, C., and Yu, L.: Modeling the effects of management intensification on multiple forest services: a Swedish case study, Ecological modeling, 284, 48–59, 2014

Åström, S., et al. (2013). "Potential impact on air pollution from ambitious national CO2 emission abatement strategies in the Nordic countries – environmental links between the UNFCCC and the UNECE – CLRTAP." Energy Policy 53: 114-124.

CLEO's researchers and co-authors

IVL Swedish Environmental Research Institute (IVL) John Munthe (programme coordinator), Jenny Arnell, Filip Moldan, Per Erik Karlsson, Stefan Åström, Tomas Gustafsson, Karin Kindbom, Sofie Hellsten, Karin Hansen, Sara Jutterström, Maria Lindblad, Haben Tekie, Mikael Malmaeus, Johanna Stadmark.

SMHI Joakim Langner, Berit Arheimer, Göran Lindqvist, Magnuz Engardt, René Capell, Thomas Bosshard, Camilla Andersson, Robert Bergström, Manu Thomas, Lars Gidhagen, Helén Andersson, Charlotta Pers, Johan Strömqvist; Jonas Olsson, Wei Yang and Kean Foster.

The Swedish University of Agricultural Sciences (SLU) *Department of Aquatic Sciences and Assessment* Kevin Bishop, Staffan Åkerblom, Johan Temnerud, *Department of Soil and Environment* Annemieke Gärdenäs, Martin Rappe George, Linnea Hansson

University of Gothenburg *Department of Biological and Environmental Science* Håkan Pleijel *Department of Chemistry and Molecular Biology* Matthias Hallqvist

Lund University (LU) *Department of Physical Geography and Ecosystem Science* Cecilia Akselsson, Jörgen Olofsson, Veronika Kronnäs

Stockholm University (SU) *Department of Applied Environmental Science* Hans-Christen Hansson

Uppsala University Julia Hytteborn

Climate Change and Environmental Objectives

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How will climate change impact the possibilities of reaching the Environmental Quality Objectives Clean Air, Natural Acidification Only, Zero Eutrophication and A Non-Toxic Environment?

The research program CLEO – the Climate Change and Environmental Objectives research programme – provides answers to questions related to the identified Environmental Quality Objectives, as well as potential synergies and conflicts between management strategies för air pollution and climate, including the effects of increased bioenergy use.

Within CLEO, a number of tools and models have been developed and applied to judge how climate change, future air pollution and the development of forestry will affect the environmental status of the air, forest and surface waters.

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NATUR VÅRDS VERKET

Swedish EPA SE-106 48 Stockholm. Visiting address: Stockholm - Valhallavägen 195, Östersund - Forskarens väg 5 hus Ub, Tel: +46 10 698 10 00, fax: +46 10 698 10 99, e-mail: registrator@swedishepa.se Internet: www.swedishepa.se **Orders** Ordertel: +46 8 505 933 40, orderfax: +46 8 505 933 99, e-mail: natur@cm.se Address: CM Gruppen, Box 110 93, SE-161 11 Bromma. Internet: www.swedishepa.se/publications