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Consequences of intensive forest harvesting on the recovery of Swedish lakes from acidification and on critical load exceedances

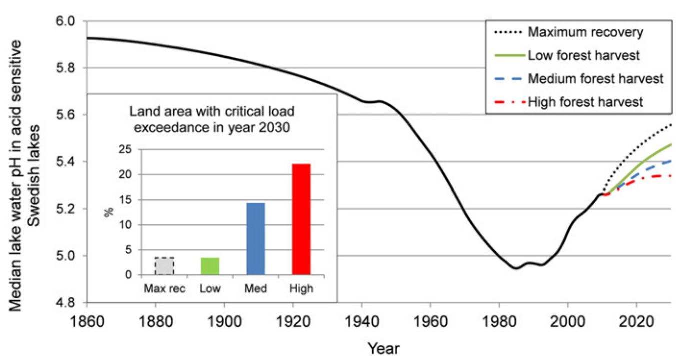
Filip Moldan [a,*], Johanna Stadmark [a], Jens Fölster [b], Sara Jutterström [a], Martyn N. Futter [b], Bernard J. Cosby [c], Richard F. Wright [d]

[a] IVL Swedish Environmental Research Institute, Box 530 21, 400 14 Göteborg, Sweden
[b] Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Lennart Hjelms väg 9, 750 07 Uppsala, Sweden
[c] Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Road, Bangor LL61 6HJ, United Kingdom
[d] Norwegian Institute for Water Research, Gaustadalléen 21, NO-0349 Oslo, Norway

HIGHLIGHTS

- The impact of future forest harvesting on the chemistry of 3000 Swedish lakes was studied.
- Intensive forest harvesting causes high rates of base cation removal from soils.
- Depending on harvesting practices, lake acidification recovery may continue, stabilize or reverse.
- More forest harvest results in more exceedance of critical loads at same deposition.

GRAPHICAL ABSTRACT



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ABSTRACT

Across much of the northern hemisphere, lakes are at risk of re-acidification due to incomplete recovery from historical acidification and pressures associated with more intensive forest biomass harvesting. Critical load (CL) calculations aimed at estimating the amount of pollutants an ecosystem can receive without suffering adverse consequences are dependent on these factors. Here, we present a modelling study of the potential effects of intensified forest harvesting on re-acidification of a set of 3239 Swedish lakes based on scenarios with varying intensities of forest biomass harvest and acid deposition. There is some evidence that forestry would have caused a certain level of acidification even if deposition remained at 1860 levels. We show that all plausible harvest scenarios delay recovery due to increased rates of base cation removal. Scenario results were used to estimate critical loads for the entire population of lakes in Sweden. The forestry intensity included in critical load calculations is a political decision. After scaling calculations to the national level, it was apparent that a high but plausible forest harvest intensity would lead to an increase in the area of CL exceedances and that even after significant reductions in forest harvest intensity, there would still be areas with CL exceedances. Our results show that forest harvest intensity and regional environmental change must be carefully considered in future CL calculations.

* Corresponding author.
E-mail address: filip.moldan@ivl.se (F. Moldan).

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1. Background

In many regions of Europe and North America, there is an ongoing legacy of surface water acidification related to historic acid deposition (Evans et al., 2001; Garmo et al., 2014). In the second half of 20th century much of Fennoscandia received large amounts of sulphur (S) emitted from fossil fuel combustion and industrial processes in northern and central Europe. As a consequence, soils and surface waters in southern Sweden, Norway and Finland gradually acidified. Many lakes lost fish populations (Tammi et al., 2003) and the long-term fertility of soils has been put at risk (e.g. Tamm, 1976; Akselsson et al., 2006). While acid deposition is well below historical highs, modelling studies have suggested that more intensive forest harvesting for bioenergy production may slow or counteract recovery (Akselsson et al., 2006; Iwald et al., 2013). Removal of the essential base cations (BC; Ca + Mg + K) in forest biomass will reduce the buffering capacity of the catchment soils and may make surface waters more sensitive to acidification.

In Sweden, the criterion for surface water acidification is based on the estimate of change in lake (or stream) pH between reference conditions, assumed to exist in 1860 when there were only minor industrial impacts on the environment, and the present. A decrease of pH (ΔpH) of > 0.4 units is considered indicative of unacceptable biological damage and is used for the classification of ecological status in Sweden (Naturvårdsverket, 2007). This criterion is derived from empirical data for sensitive fish populations and littoral invertebrates (Fölster et al., 2007). Reference condition pH is modelled either directly with the dynamic model MAGIC (Model of Acidification of Groundwater In Catchments; Cosby et al., 1985a, 1985b, 2001) or indirectly by comparison with a similar water body that has been modelled by MAGIC and stored in the MAGIC library (Moldan et al., 2013a, 2013b).

The extent to which surface water pH has changed between the reference condition and the present depends on both past air pollution and land management in the catchment. The MAGIC model uses present-day observed lake (or stream) water chemistry and soil chemistry for calibration of several soil parameters such as mineral weathering and pre-industrial soil base saturation. Historical changes in acid deposition and forestry practices must be specified to reconstruct time series of water and soil chemistry between reference conditions and the present day. Credible future projections are dependent on both realistic descriptions of the past to calibrate the model and on realistic projections of the future acid deposition and land use.

The 2009 European Renewable Energy Directive requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. Several European countries, including Sweden, have interpreted the Directive to promote a greater reliance on bioenergy from trees. Estimates of the effects of acid deposition and current and future forest harvesting on surface water acidification are needed to ensure that more intensive forest harvest does not lead to unacceptable environmental consequences.

The Convention on Long-range Transboundary Air Pollutants (CLRTAP) is an international body that among other things seeks to reduce the emissions of acidifying air pollutants including sulphur and nitrogen (N). Protocols have been "effects- based" and aim to reduce the deposition of S and N compounds such that the critical loads (CL) to terrestrial and aquatic ecosystems are not exceeded (UNECE, 2015). The CL concept is based on the idea that an ecosystem has a threshold for the amount of pollutants it can receive before suffering unacceptable damage (Nilsson and Grennfelt, 1988; CLRTAP, 2004). Thus, the CL concept provides a link between air pollution and effects. The CL concept makes the implicit assumption that land use is static while in reality higher BC removal rates associated with more intensive forest harvesting will leave less buffering capacity in the soils to counteract acidifying atmospheric deposition, and if included in the calculations will result in lower CLs.

Within the CLRTAP, each country can choose the method by which the critical loads are determined to best suit the national conditions. This includes decisions about the future intensity of forest harvesting and other possible land use in CL calculations. Declines in acid deposition since the peak in the 1980s means that assumptions about the intensity of forest harvesting used in CL calculations have become increasingly important. This is because BC loss from soils due to acid deposition and leaching to runoff has declined relative to BC removal associated with forest harvesting. Since the 1980s when the first critical load calculations for Sweden were made, S deposition has decreased by > 80% while the intensity of forest harvesting, especially whole tree harvesting, has increased. The relative importance of forest harvesting for BC removal from soils has therefore become much larger and consequently, the choice of forest harvest scenarios has become more important for the outcome of CL calculations. The projected increasing intensity of forest harvesting implies increasing exceedance of critical loads at constant - or even at decreasing – acid deposition.

While future forest harvesting practices are subject to many economic, technical and environmental constraints, and thus are by no means certain, most scenarios suggest significant increases in harvest intensity (Claesson et al., 2015). Here we used five different forest harvest scenarios as inputs to the MAGIC model and calculated critical loads from these scenarios for a dataset of 5084 Swedish lakes.

2. Materials and methods

2.1. Lakes in this study

In Sweden, there are about 100,000 lakes larger than 1 ha (http://www.smhi.se/k-data/hydrologi/sjoar_vattendrag/sjo_SVAR_2009.pdf). A set of 3239 Swedish lakes were calibrated with MAGIC when building the 2012 version of the MAGIC library (Moldan et al., 2013a). The MAGIC library (Moldan et al., 2013b) regionalizes individual MAGIC simulations using an analogue matching procedure based on 10 parameters describing lake geographical position, surface area, measured or estimated annual discharge and observed lake water chemistry. The MAGIC library consists of two key components: a library of the existing MAGIC model runs and an analogue matching routine which selects the library lake which is most similar to an evaluation lake described by the 10 parameters. The acidification assessment modelled by MAGIC at the library lake is then assumed valid for the evaluation lake as well (http://magicbiblioteket.ivl.se/, Moldan et al., 2013b). The MAGIC library version 2012 (MAGIC $library_{2012}$) was used in this study.

Water chemistry data for the 3239 library lakes comes from three separate lake surveys. These are 163 "time series" lakes, 1625 "liming reference" lakes and 1451 "national survey" lakes (Fölster et al., 2014). The liming reference lakes and most of the time series lakes were selected because they are acid sensitive. Therefore, the 3239 modelled lakes represent a subset of Swedish lakes biased towards acid sensitive lakes.

To estimate CLs for the whole of Sweden we used the entire 5084 lakes in the national lake survey (Fölster et al., 2014). The national survey lakes are a stratified random selection such that they provide the basis for making estimates for the entire population of Swedish lakes. Stratification was based on lake size class and geographic location (Grandin, 2007).

2.2. The MAGIC model

MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on soils and surface water chemistry (Cosby et al., 1985a, 1985b, 2001). Details of the soil data aggregation and deposition calibration procedure of the MAGIC application used here are given in Moldan et al. (2013a).