A paleolimnological perspective on liming – implications for defining reference conditions in Swedish lakes

Matilda Norberg

Akademisk avhandling

som med vederbörligt tillstånd av Rektorsämbetet vid Umeå universitet för
avläggande av filosofie doktorsexamen i miljövetenskap
kommer att offentligt försvaras i sal KB3A9 (Lilla hörsalen), plan 3, KBC-huset,
Umeå universitet, fredagen den 24 april 2009, kl.10.00.
Avhandlingen kommer att försvaras på engelska.

Examinator: Professor Ingemar Renberg
Fakultetsopponent: Doktor Helen Bennion, Environmental Change Research Centre,
Department of Geography, University College London

Department of Ecology and Environmental Science
Umeå University
Umeå 2009

Organization
UMEÅ UNIVERSITY
Department of Ecology and Environmental Science
SE-901 87 Umeå,
Sweden

Document name
Doctoral dissertation

Date of issue
April 2009

Author
Matilda Norberg

Title
A paleolimnological perspective on liming – implications for defining reference conditions in Swedish lakes

Abstract
Using paleolimnological techniques, I have studied surface-water acidification and the effects of liming in Swedish lakes on a decadal to millennial time-scale. The overall objective was to contribute to the discussion on the fulfilment of goals within the Swedish liming program. One of the main goals of this program is to restore lakes to natural or nearly natural conditions, i.e. to a reference condition as termed in the EU Water Framework Directive. In this context, a key issue is to define reference conditions. This is a central theme of my thesis, as lake sediments offer a unique way to study past lake conditions.

Past lake-water acidity of 12 reference lakes in the Swedish liming program (ISELAW) was determined using diatom analysis of sediment cores. Pollen, lead, and flyash from coal/oil combustion were used as indicators of impact from land use and atmospheric pollution. A general trend in these lakes is an initial decline in pH after lake formation due to natural soil processes, which was then followed by rather low pH values (pH 5.3-6.5). In six of the lakes pH increased as a result of expansion of agriculture (burning, forest grazing) 2000 to 1000 years ago. Local mining and long-range airborne pollution have also impacted the lakes since medieval time. These results show that the conditions of the study lakes were not natural prior to industrialization and recent (20th century) acidification.

The ISELAW lakes were selected on the basis of representing typical limed lakes, and they have been limed and monitored since at least the 1980s. A comparison of chemical/biological monitoring data and the paleolimnological data gives somewhat diverging results. Most of the monitoring data suggest that the lakes were subjected to acidification during the 20th century, but the paleolimnological data can only identify clear evidence of acidification in five of the 12 lakes, hence, all lakes were probably not recently acidified. According to conclusions from monitoring the lakes have recovered following liming. The paleolimnological data give a more complex picture and three different responses have been identified: 1) a return to a diatom composition found in the lake one hundred to several thousand years ago; 2) very small shifts in the diatom composition; or 3) a diatom composition previously not found in the lake. The latter response raised the question whether liming can cause an unnatural diatom community. A comparison of diatoms in surface sediment samples of 31 limed lakes with pre-industrial reference samples from 291 lakes showed that liming does not create an unnatural diatom composition. These results illustrate that the goals for liming were not reached in all of the limed lakes, and that paleolimnology can play an important role for assessments of acidification and liming. The comparative study also highlights the importance of designing monitoring programs that can produce reliable and long data series.

Given the results of the paleolimnological investigations, it is obvious that we cannot assume that the 19th century represented a natural or near natural state, and thus is a realistic reference conditions. Natural long-term lake development and previous land-use impacts need to be considered in defining reference conditions. Neither can we disregard the fact that humans always will impact nature. Although paleolimnological studies are time consuming, I believe that they could be simplified to the extent that paleolimnology could become a routine method for environmental management.

Key words: Acidification, Liming, European Water Framework Directive, Reference condition, Diatoms, Paleolimnology, Monitoring, Lake sediments

Language: English **ISBN:** 978-91-7264-761-9 **Number of pages:** 14+ 4 papers

Signature: **Date:** 2009-03-31

A paleolimnological perspective on liming – implications for defining reference conditions in Swedish lakes

Matilda Norberg

Department of Ecology and Environmental Science
Umeå University

Umeå 2009

ISBN 978-91-7264-761-9

Printed by VMC, KBC, Umeå University, Umeå, 2009

List of papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

I. Guhrén[1] M, Bigler C, Renberg I (2007) Liming placed in a long-term perspective: A paleolimnological study of 12 lakes in the Swedish liming program. Journal of Paleolimnology 37:247-258

II. Norberg M, Bigler C, Renberg I (2008) Monitoring compared with paleolimnology: implications for the definition of reference condition in limed lakes in Sweden. Environmental Monitoring and Assessment 146:295-308

III. Norberg M, Bigler C, Renberg I. Does liming to mitigate acidification restore the natural diatom community in Swedish lakes? Implications for defining realistic reference conditions. Submitted to Journal of Paleolimnology

IV. Renberg I, Bigler C, Bindler R, Norberg M, Rydberg J, Segerström U. Environmental history: A piece in the puzzle for establishing plans for environmental management. Journal of Environmental Management. Accepted for publication

[1] In 2007 my surname was changed from Guhrén to Norberg

Contents

Introduction

Surface water acidification due to acid deposition was recognized as a threat to life in lakes and watercourses in the 1960s and 1970s (Odén 1967; Jensen and Snekvik 1972; Almer et al. 1974). Since then, thousands of lakes and watercourses in Scandinavia, Great Britain and North America have been classified as acidified. To prevent acidification, the international community made great efforts to reduce emissions of sulfur and other pollutants, resulting in the Convention on Long-Range Transboundary Air Pollution, signed by 49 countries in 1979. Since then a number of programs have been initiated and further policy decisions have been made aimed at reducing the emissions of acidifying compounds. Several monitoring programs, covering both chemical and biological parameters, have been launched in Scandinavia (Moldan et al. 2001; Skjelkvåle et al. 2001), Canada (Jeffries et al. 2003) and the UK (Monteith and Evans 2005), and international monitoring activities (Kvaeven et al. 2001; Skjelkvåle et al. 2005) have been initiated with the aim of evaluating the degree and geographical extent of acidification as well as determining whether recovery has occurred following reductions in acid deposition. In the 1990s concerns were raised that the extent of acidification had been overestimated, for example, that many lakes in northern Sweden were naturally acidic (Ivarsson and Jansson 1995; Korsman 1999; Laudon et al. 1999) .

In 1976 a liming program to counteract acidification was initiated in Sweden and since then 8,000 lakes and 12,000 km of watercourses have been limed (Appelberg and Svenson 2001). Several thousand sites in Norway (Sandøy and Langåker 2001) have also been treated in an extensive liming program, and in Finland, Great Britain, the USA and Canada liming has been performed at some sites, however, on a more experimental scale than in Sweden and Norway (Henrikson and Brodin 1995). The main goals of liming in Sweden are to prevent acidification from taking place in acid-sensitive surface waters until acid deposition is reduced, or to restore natural conditions in acidified waters (Swedish Environmental Protection Agency, 2009). The original restoration goals were pH >6 and alkalinity >100 $\mu eq\ L^{-1}$ (Bernes 1991); however, these goals were later modified and today there are three different pH-categories (pH 5.6, 6.0 and 6.3) based on biological indicators (Swedish Environmental Protection Agency 2002). In the 1990s when it became obvious that many lakes were naturally acidic, concern was expressed about the risk that not only surface waters that were anthropogenically acidified were being limed, but also naturally acid waters. Several studies indicated that naturally acid lakes and watercourses in the northern part of Sweden had been limed, and Bishop et al. (2001) criticized the lack of effort to include these findings in management plans.

A national program called Integrated Studies of the Effects of Liming Acidified Waters (ISELAW) was initiated in 1989 in Sweden. The objectives were to assess long-term chemical and biological effects of liming, i.e. to study whether limed ecosystems recover to a pre-acidified state, and to identify possible detrimental effects of liming (Appelberg and Svenson 2001). Until 2005, when the program was expanded, it comprised 13 lakes chosen to represent typical limed lakes in Sweden. In those lakes, water chemistry, phytoplankton, zooplankton, macroinvertebrates and fish are monitored on a regular basis (www.ma.slu.se).

In 2000 the European Parliament and Council established a framework for water legislation in Europe – the European Water Framework Directive (WFD) (European Union 2000). According to this directive, all waters should have reached a "good" status before 2016. The status of a water body is defined as good when there are 'low levels of distortion resulting from human activity, but deviating only slightly from those normally associated with the surface water body type under undisturbed conditions' (European Union 2000). More commonly, this status is referred to as the reference condition. The definition of reference condition has been thoroughly analyzed in conjunction with the implementation of the WFD, and the complexity of defining a reference condition with respect to naturalness, reasonable management efforts and costs has been highlighted elsewhere (Johnson 2001; Owen et al. 2002; Wallin et al. 2003). In order to reach and control the requisite good status in all surface waters, the WFD requires the establishment of extensive monitoring programs.

Most monitoring programs in Sweden were initiated when it was recognized that surface water acidification due to acid deposition was occurring or at the time when liming programs were launched; monitoring data from earlier periods are, therefore, usually scarce. To be able to identify if and how lakes have been affected by acidification and liming as well as to define realistic reference conditions, longer time scales need to be considered. In the work of this thesis, paleolimnological methods were used to address these questions over a time scale ranging from decades to millennia. Paleolimnological studies offer the only means of studying the biology and chemistry of a lake and its catchment in the past, prior to the existence of written sources and the initiation of monitoring programs (Smol 2008).

The main paleolimnological indicators used in the investigations associated with this thesis are diatoms. Diatoms have qualities that make them excellent indicators of past changes in lake ecosystems and, for nearly a century, they have been used as environmental indicators (Stoermer and Smol 1999; Smol et al. 2001).

Objectives

The main aims of this thesis were to analyze the ways in which a number of limed lakes have been affected by natural and human induced processes in the past, focusing on lake-water acidity, how liming to mitigate acidification has affected the lakes, whether the limed lakes have reached a reference condition, and finally, what constitutes a realistic reference condition. The following specific questions are addressed within the thesis:

- What was the natural condition of limed lakes within the ISELAW program, with emphasis on their acidity status?
- What was the history of human impact on the ISELAW lakes?
- Were the studied limed lakes acidified due to acid deposition during the industrial period?
- Do the monitoring and paleolimnological data agree on the magnitude of acidification and the effects of liming in the lakes during the 20th century?
- Have the goals for liming been achieved in the ISELAW lakes?
- Does liming cause an unnatural condition in lakes, i.e. is the ecosystem produced as a result of liming one that never occurred in Swedish lakes in the past?
- How can we define a realistic reference condition in lakes affected by human activities?

Study sites

Twelve of the thirteen ISELAW lakes have been studied with paleolimnological methods. They are situated in southern Sweden (Papers I and II). Long sediment cores from these lakes were sampled in the winters between 1999 and 2003. Surface sediments from other limed lakes (Paper III) were sampled from a boat in autumn 2007. Overall, the data set includes 31 lakes that have been continuously limed either directly on the surface or indirectly via upstream lakes, inlets and wetlands over a period of at least 10 years.

Reference sediments, i.e. pre-industrial sediment samples from 291 reference lakes (Paper III), have been sampled by researchers from the Environmental Change Assessment research group (Umeå University) on a number of occasions during the last 25 years (Renberg and Hultberg 1992; Renberg et al. 1993a; 1993b; Korsman et al. 1994; Korsman and Birks 1996; Ek and Korsman 2001; Ek and Renberg 2001; Guhrén et al. 2003). All lakes are situated on granitic bedrock with shallow soils and the vegetation in the catchments is mainly dominated by Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pubescens*). The lakes are typically between 0.01 km^2 and 7 km^2 in area and have a maximum depth between 2 m and 47 m.

Materials and methods

Recent sediments (0-40 cm depth) were sampled with a HTH sediment corer (Renberg and Hansson 2008) or a modified version of the freeze corer described by Renberg and Hanson (1993). Deeper sediments were sampled with a Russian peat corer (Glew et al. 2001). The cores were usually taken in the deepest basin of each lake. The cores taken with the HTH sediment corer were sub-divided directly into containers, normally into 0.5 or 1 cm increments. The sediment cores taken with a freeze corer or a Russian peat corer were sub-sampled in the laboratory.

Diatom samples were prepared following standard procedure (Battarbee 1986; Renberg 1990). A total of 200-600 diatom valves were counted in each sample and identified, principally following the taxonomy of Krammer and Lange-Bertalot (1986-1997) and Stevenson et al. (1991). For Papers I, II and IV, diatom-based pH reconstructions were performed with weighted averaging regression and calibration using the software CALIBRATE version 0.81 (Juggins and ter Braak 1997). Two different diatom calibration data-sets were employed: the SWAP data-set with a bootstrapped root-mean-square-error of prediction (RMSEP) of 0.32 pH units (Stevenson et al. 1991) and the data-set of Korsman and Birks (1996) with a jack-knifed RMSEP of 0.36 pH units. Ordination analyses, performed with the computer program CANOCO version 4.5 (ter Braak and Šmilauer 2002), were used in Papers I and III. In Paper I a linear species response model, i.e. Principal Component Analysis (PCA) (Pearson 1901), and in Paper III a Detrended Correspondence Analysis (DCA) (Hill and Gauch 1980), were used. In Paper I Simpson's index (1-D) was used as a measure of diversity (Washington 1984). In Paper III, analogue matching was carried out using the computer program C2 data analysis version 1.4.3 (Juggins 2005) with squared chord distances (Overpeck et al. 1985).

In Paper I, analysis of lead and flyash particles (SCP - Spheroidal Carbonaceous Particles) was carried out. Lead analyses – concentrations (µg g^{-1} dry sediment) and stable isotope ratios ($^{206}Pb/^{207}Pb$) – followed standard procedures (Brännvall et al. 2001), and SCP analysis (number of particles g^{-1} dry sediment) followed the method described in Wik and Renberg (1996). In addition, pollen analysis was carried out, and both preparation and analysis followed Moore et al. (1991).

The monitoring data used in Paper II was provided by the Department of Aquatic Science and Assessment at the Swedish University of Agricultural Sciences in Uppsala (www.ma.slu.se), acting as a data host for the Swedish Environmental Protection Agency. Included in the monitoring data, which has been collected since 1989, are benthic invertebrates and fish (sampled once a year), zooplankton (sampled monthly in the summer) and pH-measurements (sampled at least once a month). Also some biological and water chemistry data collected from the late 19th century until 1989 are available.

A brief description of the content of the papers

Paper I examines the long-term history of 12 of the lakes in the ISELAW program; the specific aims were to define natural lake conditions and study the effects of early human impact, acidification, and liming. Diatom analysis was used to assess how diatom communities changed in the lakes from ancient times until the present, and to infer past lake-water pH conditions. Pollen analysis was used to study vegetation change and land use history; lead and flyash particles (SCP) were used as indicators of the impact of airborne pollution.

Paper II compares the monitoring data from 12 of the ISELAW lakes with data from the paleolimnological investigations in order to assess how well the two methods agree with respect to the rate of recent acidification and the effects of liming. Based on this comparison, questions about defining reference conditions, acidification, and restoration by liming are addressed.

Paper III compares diatom species composition in the surface sediments of thirty-one limed lakes with the diatom species composition in a reference data set of sediment samples from pre-industrial times in 291 Swedish lakes. The aim was to assess whether liming creates a unique

diatom composition that has never occurred in Swedish lakes before. Also addressed is the issue of what constitutes a realistic reference condition.
Paper IV summarizes five paleolimnological case-studies to discuss the benefits of examining a longer time perspective in environmental management. This paper contributes to the thesis by the case-study on acidification and liming and the associated discussion.

Results and discussion

The history of natural and human induced changes in the lakes
In six of the limed lakes in the ISELAW program, according to the diatom analyses (diatom-inferred pH), a period of higher lake-water pH began between 2000 and 1000 years ago. This alkalization period was the result of land-use, mainly forest burning and livestock grazing, as evidenced by pollen from anthropocores (herbs and graminoids introduced by man) and apophytes (shrubs, herbs and graminoids favored by man). Other ISELAW lakes are situated in areas where mining has been practiced during the last millennium. These lakes are affected by regional pollution emissions and probably also by land-use related to mining, for example timber cutting (Törnqvist 2008). In addition, all lakes in Sweden, and particularly in southern Sweden, have been affected by considerable amounts of long-range airborne pollution since at least medieval times (Renberg et al. 2000; Brännvall et al. 2001; Bindler et al. 2002). Besides human impact, the lakes have gone through natural changes during the course of the Holocene (lake ontogeny), which have also affected lake acidity. In the lakes where the entire Holocene sediment deposit (or at least a substantial part of it) was recovered, an initially high pH (6.5-7.3) was in most of the lakes followed by a slow decline in pH during the first millennia caused by the development of soils and peatlands, reaching a pH of 5.3-6.5. This lower pH usually persisted until it was increased by human land-use activities in the catchments or it was decreased by acid deposition in the 20th century. The latter was observed in five of the twelve ISELAW lakes.

Since liming in all of the twelve lakes was initiated because they, according to the criteria for selection, were subjected to acidification in the 20th century, it was a surprise that the paleolimnological analysis only detected recent acidification in five of them. Even though there are possible problems and limitations with paleolimnological investigations, such as mixing and relocation of the sediment in the lakes or very low sedimentation rates concealing shifts caused by recent acidification, this cannot fully explain why there were no clear acidification signals in the recent sediments of seven of the lakes. Probably, several of the lakes were not recently acidified. In Paper IV the long-term impact of human activities on lakes is further emphasized. Similar shifts in pH as detected in the ISELAW lakes, caused by natural development and human impact, have been described previously for many Swedish lakes (Renberg et al. 1993b; Paper IV).

Comparison of data from monitoring and paleolimnology, and fulfillment of liming goals
According to the monitoring data from the ISELAW program, all twelve lakes were acidified due to acid deposition in the 20th century, and hence, liming was initiated as a mitigation measure. However, the available lake monitoring data, pertaining to fish, benthic invertebrates and zooplankton are scattered, in many of the lakes they are completely lacking, and sometimes they are even contradictory during the pre-liming period. Even though pH measurements are usually more common than biological data, measurements are still scarce and irregular in many of the lakes, and in two lakes, no measurements from the time prior to liming were available. When comparing measured and diatom-inferred pH from the period prior to liming the measured pH values in five lakes are within the margin of error of the reconstructions, and for five lakes the difference between measured and diatom-inferred pH is more than 1 pH unit. When monitoring data are comprehensive, the agreement between the two methods improves, which may demonstrate the problem of drawing conclusions from fragmentary data sets. During the liming period the monitoring data shows recovery of the fish population in all lakes except one. However, as pointed out by Reizenstein (2000), it is difficult to draw unambiguous conclusions about the reasons for changes in fish populations, especially since many fish species had been

stocked into the ISELAW lakes. The number of taxa and the abundance of acid sensitive species of zooplankton and benthic invertebrates increased in all lakes where data was recorded prior to liming (Persson and Ekström 2001). The pH measurements showed a clear increase in pH in all lakes after an initial phase of large fluctuations (Persson and Wilander 2002). The diatom-inferred pH increased in all lakes, although, in several cases, this was within the margin of error of the reconstruction model. For the liming period, the agreement between the monitored pH and the diatom-inferred pH is within the margin of error of the reconstructions in seven of the lakes, and in five lakes the discrepancy is more than 0.5 pH units. The better agreement between the two methods after liming is probably due to improved monitoring data series after the initiation of the ISELAW program.

So, have the goals of liming been achieved in the ISELAW lakes? Even though most of the monitoring data suggest that lakes have recovered after acidification, the paleolimnological data tell a different story, at least in part. Liming caused changes in the diatom communities; this can be attributed to one of three different responses: 1) a return to a diatom composition that existed previously in the lake one hundred to several thousand years ago; 2) a diatom composition previously not found in the lake; or 3) very small shifts in the diatom composition. The last response is, for example, found in Brändasjö, the examination of which is described in more detail in Paper IV. Brändasjö is a naturally acidic, brown-water lake, where no change in the diatom composition due to recent acid deposition or liming was detected, i.e. it is a lake where liming was not needed.

In several of the ISELAW lakes a diatom composition that existed earlier in the history of the lakes was established after liming. It can appear that liming has been a successful measure in these lakes; however, this is not necessarily the case. First, if a lake was not subjected to acidification in the 20th century, the liming itself is a human induced disturbance that moves the lake ecosystem away from a natural state. Second, if a lake is returned to a state that the fundamental properties of the catchment cannot currently support, such as the pristine conditions after lake formation or during ancient periods of impact from early agricultural activities or mining, that state cannot be considered to be sustainable. Without a clearer definition of what constitutes a good status in limed lakes according to the WFD, taking into consideration data quality, long-term human influence and natural development of the lakes, it is not possible to define whether such a status has been reached in the ISELAW lakes.

These results show that paleolimnology has a role to play in the assessment of acidification and liming, over both long and short time scales, especially where monitoring data are scarce. It also shows the importance of designing monitoring programs so that they produce reliable and long data series that can be evaluated effectively. This is important for practical work linked to the WFD.

In some of the ISELAW lakes, liming resulted in a diatom community that had not previously existed in the lakes. This response had already been observed by Renberg and Hultberg (1992) in their investigation of Lysevatten. This raises the question of whether liming causes an unnatural condition in some lakes, i.e. an ecosystem produced as a result of liming that never occurred in Swedish lakes in the past. However, a comparison of diatoms in surface sediment samples of 31 limed lakes with pre-industrial reference samples from 291 lakes showed that liming does not create an unnatural diatom composition.

Time-perspective and defining reference conditions

The history of human impact on the lakes is longer than assumed in most programs of measure. Usually the 19th century is considered to be a period when lakes were in a relatively unaffected condition (Swedish Environmental Protection Agency 2007). In the paleolimnological studies presented in this thesis it was clearly demonstrated that the use of the 19th century as a reference is questionable. So, what is a realistic reference condition to aim at in order to fulfill the goals of the WFD, i.e. to establish a condition that corresponds to low levels of distortion resulting from human activity (a natural lake), and at the same time to achieve this at a realistic cost and level of management? First, a longer time-perspective needs to be considered. In Paper I the condition that existed a few thousand years ago, prior to extensive agricultural land-use, was suggested as a natural reference condition. However, lakes need to be considered individually on a site-specific basis. Each lake has its own local history of human activities such as agriculture, mining and forestry. In some lakes the 19th century might represent a state that can be considered to constitute a reference condition in the spirit of the WFD definition; in other lakes a perspective of several hundred up to several thousand years is necessary to find a site-specific reference condition.

When a site-specific reference condition, in the sense of the condition that existed prior to extensive human impact, has been defined, it can appear to be a realistic reference condition to aim for in programs of measure. However, a strict site-specific reference condition does not take full account of lake ontogeny and contemporary anthropogenic impact. Since ecological systems are dynamic, a condition that existed hundreds to thousands of years ago would probably not exist naturally today, even without impact from, for example, anthropogenic acidification. In addition, even though a condition representing low levels of distortion resulting from human activity represents good status in terms of the WFD, we cannot ignore the fact that the current state of the landscape is, to a large extent, a product of human impact in the past. To be able to define a realistic reference condition, the effect of a certain level of human activity has to be considered.

I argue that the site-specific reference condition should be evaluated against a general reference data set, as described in Paper III. However, a general reference data set, including information from hundreds of lakes distributed over a large geographical area and lakes of many different types could lead to a pointless evaluation, since almost all limed lakes will have an analogue in such a data set. Hence, a reference data set comprising lakes subdivided into classes with appropriate lake and catchment characteristics, reflecting the chemical or biological variable under consideration should be used. Such a type-specific reference condition is recommended within the WFD and has been applied in studies defining reference condition in eutrophic lakes in the UK (Bennion et al. 2004).

A somewhat similar approach is also taken within the current classification of impact of acidification on Swedish lakes, where the hydrogeochemical model MAGIC is used (Swedish Environmental Protection Agency 2007). The paleolimnological approach and MAGIC modeling are two different ways of answering the same question, namely what is a realistic reference condition? Hence they can complement each other; where a lack of data makes MAGIC modeling uncertain paleolimnological methods can be applied and *vice versa*. The difference in approaches, with MAGIC using hydrogeochemical data from the lake catchment and paleolimnology using biological remains in the sediment, also results in the two methods providing different benefits. For example, paleolimnological studies can provide a time-perspective of several thousand years, as shown in this thesis, and MAGIC can provide a good estimate of the natural variability in lake pH on a seasonal to decadal time-scale (Erlandsson et al. 2008) where monitoring data is lacking.

Following the recommendation outlined above, a more realistic reference condition could be defined, using paleolimnological investigations. Initially the cost of establishing such a reference condition may seem high. On the other hand, unnecessary management costs resulting from unrealistic goals can be avoided.

The discussion about defining a realistic reference condition does not only concern limed lakes, but all lakes that have experienced changes caused by human activities. It is essential to incorporate a long-term perspective in all environmental planning and management, when establishing monitoring programs and in defining reference conditions to set realistic goals and manage lakes so that they attain a sustainable condition.

Filling the gaps – future perspectives

Because there are different responses to the liming of lakes and my data set is relatively small, it would be valuable to study a larger number of limed lakes using paleolimnological methods. Building up such a data set opens up opportunities for categorizing the lakes, and defining the type of lake in which a diatom assemblage will respond in a certain way. This might allow us to identify lakes where liming can be terminated since no human induced acidification has occurred or where liming does not fulfill the goals of establishing a natural system. In this way, for example, natural systems adapted to slightly acidic conditions would be maintained and the money spent on liming could be directed to necessary environmental management. Such a project could include the 40 lakes in the expanded ISELAW program, launched in 2005. Monitoring data are more extensive for these lakes than for Swedish lakes in general. In addition, sediment cores already collected from about 20 limed lakes sampled in 2007 (Paper III) but not yet analyzed for historical trends could be included. Liming has been conducted on a large scale and over a long time in Sweden, and these limed lakes offer a unique opportunity to study ecological effects of abrupt changes in lake-water pH and the chemical composition of the water. Furthermore, an extensive database derived from paleolimnological studies of limed lakes would provide an opportunity to learn more about how to establish large scale programs of measures and management plans directed towards other environmental problems, in a sustainable way.

In a pilot assessment, not presented in this thesis, I found that lake size, maximum and mean depth, secchi depth (few measurements), altitude and geographical coordinates explained very little of the variation in diatom composition in the reference data set used in Paper III. In lakes in the UK it has been shown that lake size and depth are important factors in categorizing lakes for defining a reference trophic level (Bennion et al. 2004). I would like to determine which factors need to be taken into consideration when classifying lakes into acidity-related classes. Appropriate classification of lakes is important for defining realistic reference conditions. The importance of the correct classification of lakes is stressed in a new extensive project that will be launched at the end of 2009 by the Swedish Environmental Protection Agency.

Undertaking a series of diatom analyses in a sediment core is time consuming, and expert knowledge is required. To be able to incorporate diatom analysis of sediments on a more regular basis in the monitoring of surface waters and in defining reference conditions, the method needs to be developed to reduce the effort and costs to a more realistic level. Experience from, for example, analyses of chironomids (Heiri and Lotter 2001; Larocque et al. 2001), show that in most cases the outcome of the analyses (e.g. inferred pH) is dependent on a few dominant species, suggesting that analyses could be simplified. In a Swedish report by Gälman et al. (2009), dealing with classification of water quality in streams in accordance with the WFD in the county of Västerbotten (northern Sweden), it was suggested that only 40 diatom valves needed to be counted per sample at most sites for a reliable classification. It was also suggested that the taxonomic resolution could be reduced and taxa occurring in low abundances could be excluded without adversely affecting the classification. A similar approach is probably applicable to the analysis of sediment profiles in lakes. Besides evaluating how diatom analysis could be more efficient it would also be interesting to analyze how many pre-industrial sediment samples are needed to give reliable results pertaining to the natural development of lakes and human impact on them during the last millennia. Finding a way to implement diatom analysis of sediments in monitoring programs, in the practical work with defining reference conditions and in designing programs of measure would improve the quality of such work, adding all the benefits of the paleolimnological approach.

Diatoms are only one of many kinds of biological remains in lake sediments and different organisms provide valuable information about past environmental conditions. For example, Bigler et al. (2006) showed that fossil remains of diatoms, chironomids and cladocerans in the surface sediment of 30 lakes in the Engadine area of Switzerland had potential as indictors for different environmental variables. It would be interesting to combine data relating to different sedimentary remains in order to obtain a more robust tool for identifying past natural and human induced changes in lakes, not only with respect to acidity status but also other important factors for environmental management. A combination of several proxies also gives the opportunity to differentiate between different causes of change, such as climate change and altered land-use regimes. Proxies that could be combined with diatom analysis include established techniques such as analysis of cladoceran remains (Bos and Cumming 2003; Johansson et al. 2005; Sweetman and Smol 2006), as well as promising new techniques such as inferring past lake-water color using Fourier-transform infrared spectroscopy (FTIR) and near infrared spectroscopy (NIR) (Rosén 2005; Rosén and Persson 2006).

In Paper II it was concluded that some of the limed lakes were not really suitable for paleolimnological studies. At least four confounding factors were identified: very low sediment accumulation rates reducing the time resolution of the samples; resuspension and relocation of littoral sediments; natural sediment mixing due to benthic invertebrates; and sediment mixing due to repeated sediment sampling for monitoring programs, for example, using an Ekman dredge. For future incorporation of paleolimnological investigations as a routine aspect of monitoring, it would be beneficial to address this issue further, by trying to identifying lakes where the risk of these confounding factors is high.

Acknowledgements

Special thanks to my supervisor Ingemar Renberg and my co-supervisor Christian Bigler for valuable and knowledgeable support. Thanks to Gunnar Persson at the Department of Aquatic Science and Assessment at the Swedish University of Agricultural Sciences in Uppsala, for valuable discussions and for generously sharing knowledge and data from the ISELAW program. Thanks to colleagues, field-workers and laboratory personnel for contributing to my thesis. This project was financed by the Swedish Environmental Protection Agency and The Faculty of Science and Technology, Umeå University.

Populärvetenskaplig sammanfattning

De flesta av Sveriges sjöar bildades för tusentals år sedan. Några när inlandsisen drog sig tillbaka (från 15 000 till 9 000 år sedan) och några när havet, som nu kallas Östersjön, omformades under årtusendena efter isavsmältningen. Sedan sjöarna bildades har det kontinuerligt avsatts material på botten av dem, material som har kommit via luften, marken och vattnet och består av allt från döda växt- och djurdelar till mineraler från berggrunden. Det här är geggan som silar mellan tårna när en badare sätter ned fötterna, även kallat sediment. Framför allt i djupare och lugnare delar av sjön bildar sedimentet en tidsserie där den nedersta delen är äldst och den översta yngst. Genom att provta en del av sedimentet, utan att röra om i det, kan vi studera vad som har hänt i och kring sjön sedan den bildades. Sedimentet utgör ett historiskt arkiv som inte motsvaras av något annat tillgängligt arkiv.

En av de lämningar som förekommer i sedimentet är kiselalger. Kiselalger finns i alla vatten. Har du någon gång halkat på en hal sten när du ska ta dig ett dopp är det mycket troligt att det beror på kiselalgerna som växer på stenen. Kiselalgernas skal består av kisel, därav namnet. Var och en av de hundratals arter som finns har sin egen form på skalet, vilket gör att de kan kännas igen med hjälp av mikroskop. Varje art trivs bäst i en viss miljö (t ex vad gäller pH, näringsämnen och temperatur). Genom att undersöka vilka arter av kiselalger som förekommer på en viss nivå i sedimentet, kan sammansättningen av arter översättas till ett mått på t ex vilket pH sjön har haft under den tidsperiod provet omfattar. Det är främst sådana analyser som gjorts i den här avhandlingen.

Under 1960-talet visade det sig att sjöar och vattendrag försurats av surt nedfall, vilket är ett av vår tids stora miljöproblem. För att motverka försurningen har internationella avtal skrivits på för att minska utsläppen av de försurande ämnena. I Sverige startades 1976 ett omfattande program med kalkning av sjöar och vattendrag. De huvudsakliga målen med kalkningen är att motverka effekterna av försurningen och återställa försurade sjöar till ett naturligt tillstånd.

Samtidigt som försurningen uppdagades och kalkningen startades påbörjades också övervakningsprogram. I dessa mäts t ex pH och näringsämnen och artsammansättning av fisk, bottenlevande djur, djurplankton, vattenväxter och växtplankton undersöks i utvalda sjöar och vattendrag för att se vilket tillstånd de har och hur detta tillstånd utvecklas. I de övervakningsprogram som har startats är tidsserierna inte längre än ett trettiotal år. Före det finns bara sporadiska dokumentationer från sent 1800-tal och början på 1900-talet för vissa sjöar. I början på 2000-talet kom ett direktiv från EU som kallas för vattendirektivet. I det står att alla vatten i Europa ska uppnå en god status innan år 2016. Ett referenstillstånd ska uppnås, vilket innebär att de arter som förekommer i t ex sjöar ska vara de som naturligt förekommer där. Miljön i tex sjöar ska vara naturlig och det får bara förekomma en liten påverkan från människan.

I den här avhandlingen har jag studerat kiselalger i sediment från framför allt kalkade sjöar ur ett mångtusenårigt perspektiv för att undersöka deras naturliga tillstånd, den historiska mänskliga påverkan, påverkan från försurning och kalkning, och vad ett realistiskt referenstillstånd i sjöar som påverkats av människan är.

Jag har kunnat visa att det naturliga tillståndet i de kalkade sjöarna är föränderligt. När sjöarna bildades omgavs de av landområden som var nyexponerade. Det fanns inget egentligt jordtäcke och ingen vegetation. Om ni studerat bilder på områden kring de inlandsisar som finns idag på t ex Grönland, vet ni hur det har sett ut runt dessa sjöar. Allteftersom tiden gick bildades det jordar, växter började slå rot och så småningom omgavs sjöarna av skog och myrmarker. Den utvecklingen speglas i sedimentet. Artsammansättningen av kiselalger i sedimentproverna visar att pH-värdet i början var högt och sedan sjönk det sakta under tusentals år med ca 0,1 enheter/årtusende i de flesta av sjöarna.

Jag har också kunnat visa att påverkan från människan började mycket tidigt. Ett jordbrukssamhälle växte fram för 2000 till 1000 år sedan, som framför allt bestod av skogsbete och svedjebruk. Det här påverkade närliggande sjöar. pH-värdet ökade när markerna öppnades upp och mer material och näringsämnen kunde transporteras från marken till vattnet. Flera sjöar har också påverkats av gruvverksamhet. I Bergslagsområdet har gruvverksamheten en mer än tusenårig historia. Gruvor har öppnats upp, skogarna avverkats för att utgöra bränsle i processerna för att utvinna malm, slagg dumpats både vid och i sjöarna och människor har levt i anslutning till detta. Både gruvverksamheten och det tidiga jordbruket är verksamheter som pågått i sjöarnas närhet. Även luftburet material, från gruvverksamhet i Europa, har transporterats till svenska sjöar och märkbart påverkat dem under minst 3000 år. Den mänskliga påverkan på de kalkade sjöarna är alltså flertusenårig.

Flera av de kalkade sjöar jag har undersökt är försurade av surt nedfall. pH-värdet har under 1900-talet sjunkit med 1-2 enheter under loppet av ett tiotal år. Det kan jämföras med den naturliga långsamma nedgången i pH-värdet (se ovan). Jag har kunnat visa i mina studier att det inte går att se en försurning orsakad av surt nedfall under 1900-talet i alla kalkade sjöar. I vissa sjöar är pH-värdet före kalkning visserligen lågt, men det är ett naturligt tillstånd och inte något som uppkommit under 1900-talet. I andra sjöar har pH-värdet sjunkit, men det beror till stor del på att det tidiga jordbruket som funnits i sjöns omgivning inte längre finns kvar. Sjöns pH-värde sjunker då till en tidigare nivå. I och med kalkningen har jag kunnat se att artsammansättningen av kiselalger påverkas på tre olika sätt. I en del sjöar ändras inte artsammansättningen alls till följd av kalkningen. I andra sjöar återgår den till ett tillstånd som funnits någon gång tidigare i sjöns mångtusenåriga historia och i vissa sjöar förändras artsammansättningen av kiselalger till något som inte förekommit tidigare. I en jämförelse mellan kalkade sjöar och prover från före 1900-talet i nästan 300 sjöar kunde jag dock visa att den artsammansättning som bildas efter kalkning ändå förekommit i någon svensk sjö tidigare. Utifrån de här resultaten har jag kunnat resonera kring kalkningens måluppfyllelse, om kalkade sjöar verkligen återgår till ett naturligt tillstånd. I några av de studerade sjöarna är så fallet, men i andra sjöar har kalkningen inte åstadkommit ett naturligt tillstånd.

Med utgångspunkt i mina resultat har jag fört ett resonemang om vad som är viktigt att tänka på när ett referenstillstånd ska definieras för sjöarna. I många sammanhang används mitten på 1800-talet som ett referensvärde eftersom det är före industrialiseringen. Med tanke på den långa historia av mänsklig påverkan som jag visat på i de kalkade sjöarna, kan det ifrågasättas om mitten på 1800-talet är en lämplig referensnivå. Det är följaktligen viktigt att ta med ett långt tidsperspektiv, i många fall ett flertusenårigt perspektiv, för att definiera vad som har varit ett av människan opåverkat förhållande i en sjö. Varje sjö har sin egen historia. Vissa sjöar har inte påverkats påtagligt av människan, mer än under de senaste hundra åren, medan andra har påverkats under flera tusen år. Det är således också viktigt att varje sjö bedöms individuellt. Dessutom behöver hänsyn tas till naturliga förändringar som sker i en sjö. Eftersom även det naturliga tillståndet förändras är det inte realistiskt att utse en viss tidsepok till referensnivå för en sjö. Även utan mänsklig påverkan skulle sjön inte se ut idag som den gjorde för t ex tusen år sedan. Försöker man återskapa det tillståndet i sjön idag, blir det också onaturligt. Slutligen kan nämnas att människan alltid kommer påverka miljön vi lever i, och en viss grad av påverkan måste därför få förekomma.

Genom att ta hänsyn till alla nämnda faktorer – en acceptabel nivå av mänsklig påverkan, de skiften som skett i verksamheten som bedrivits av människan och påverkat sjöarna under tusentals år, sjöarnas av människan opåverkade förhållande och den naturliga utvecklingen i sjöarna med omgivning – kan ett realistiskt referenstillstånd definieras och onödiga kostnader på grund av ohållbara åtgärder kan undvikas.

Tack

Jag vill inleda med att rikta ett stort tack till en person som jag, genom doktorandåren, blivit både frustrerad och irriterad på. Från början förstod jag honom inte. Hur skulle jag kunna få hjälp av någon som ofta tystnade som svar på en fråga? Mycket frustrerande för en pratglad och diskussionsbenägen person som jag själv. Svaren kom dock, aldrig som förväntat, alltid som otroligt träffsäkra och intelligenta synpunkter som höjde min horisont och gav mer sting och kvalitet till mitt arbete. Stor respekt har jag för den här mannen, Ingemar Renberg, som varit min handledare. Utan hans lugn, omistligt träffande synpunkter och guidning genom forskningsvärlden skulle inte min avhandling finnas, och utan hans norrländska manér skulle jag fortfarande tro att tystnad inte är ett svar.

Christian Bigler har under stor del av min doktorandtid varit min biträdande handledare. Tålmodigt har han funnits till hands och hjälpt till med allt från identifiering av trixiga kiselalger och lotsning genom datorprogram som inte vill samarbeta till ovärderlig respons på forskningsresultat och skrivna texter. ”första gången är det gratis” har han sagt, men då har jag handlat på krita väldigt länge.

Paleogruppen har bestått av och består av ett härligt gäng människor som jag vill rikta ett tack till: Jan P. för din uppfinningsrikedom med talgbollar och fläktsystem och ditt alltid lugna positiva sätt. Jonatan för din värme. Bokstavligt talat, jag tror du höjde rumstemperaturen i det kylslagna rummet flera grader, men även bildligt, den omsorg om andra människor du visar sprider värme. Anna D för alla trevliga pratstunder om allt från samhällsfrågor, kulturella skillnader, familjeliv och forskning. Laura för att du flera gånger har räddat mig när jag kört fast i analyser och formuleringar. Carola för din otroliga smittsamma energi och påhittighet. Veronika för ditt förnuft som påpekat det självklara när jag inte sett det och för att du ställt upp som min disputationsguru. Johan för att du tar tag i saker så de faktiskt blir gjorda, en sällsynt egenskap. Annika för ditt engagemang och entusiasm. Åsa för din förmåga att ingjuta mod i motgångar. Erik för hö:et och att du alltid ger ett leende och några vänliga ord i korridoren. Rich för berikande av min engelska och hjälp vid trixiga frågor. Tom för att du definierade mitt skriftspråk som blommigt och tog dig an mig som exjobbare, det var ju där allt började. Jan-Erik för att du gav mig chansen att prova på memma... som INTE är en chokladkaka! Anna E för att du efterlämnade så många användbara, lättfunna och strukturerade dokument. Cissa för föräldraguidning och andra

trevliga diskussioner. Och alla andra härliga personer – forskare, post-docs, fältassistenter och ex-jobbare – som gjort krokengänget till en mycket trevlig gemenskap att befinna sig i.

Diversiteten av personer på EMG har gjort att det har varit kul att höra till institutionen. Hur tråkiga skulle inte fikarasterna ha varit utan alla intressanta diskussionsämnen och personligheter? Det är ni som gör EMG till en trevlig och mångfacetterad institution. Tack till er alla. Ett extra tack till helt underbar administrativ och teknisk personal som får allt att gå runt. Ni är ovärderliga.

Jag vill passa på att ge en stor varm kram till mina föräldrar och syskon. Min mor Agneta som är en sådan förebild och inspirationskälla. Det finns ett uttryck som säger ”sådan mor, sådan dotter”, ett uttryck som gör mig stolt om det uppfylls. Min far Stellan med sin enorma drivkraft, som alltid visat att det går om man vill. Min bror Axel som med sin sköna stil alltid behåller lugnet. Min bror Gustaf som har härliga ambitioner både i yrkeslivet och privat. Ni har varit en bra grogrund för en doktor i miljövetenskap.

Vem vore jag utan mina vänner? Under tiden i Umeå har jag lärt känna ett stort gäng med människor som tillsammans skapat en gemenskap full med upptåg, kreativitet och samtal över en kopp te i soffan. Jag vill särskilt nämna Sandra - alltid nära oavsett avstånd, alltid sugen på att fixa, planera och inspirera, Anna P som bjudit på intressanta analyser av mer filosofisk karaktär, Johanna med sin avslappnade självklarhet i tillvaron, Lars – vår egen handyman som visar oss akademiker vad verklig praktisk begåvning innebär, Roger med alla mysiga historier från livet, Ida med ett bus i blicken, Tomas - allas vår egen doktor'n, studsbollen Josefin, Marcus som alltid lånar ut en hjälpande hand, Ferry –min skånska labbpartner och Bosse – som nästan fått mig att gilla Monty Python. Ovärderliga vänner för livet.

Min man Micke, mitt ankare och mina vingar, som ger den dos av trygghet och personlighetsutveckling i livet som jag behöver. Min son Ludvig som kom och kullkastade mitt liv och gav perspektiv på sovmorgnar och trötthet men framför allt så mycket mer färg, mening, glitter, djup, nytänkande och kärlek i livet. Ni är viktigast av allt. Tack för att ni finns.

References

Almer B, Dickson W, Ekström C, Hörnström E, Miller U (1974) Effects of acidification on Swedish lakes. Ambio 3:30–36

Appelberg M, Svenson T (2001) Long-term ecological effects of liming - The ISELAW programme. Water Air Soil Pollut 130:1745-1750

Battarbee RW (1986) Diatom analysis. In: Berglund BE (ed) Handbook of holocene palaeoecology and palaeohydrology. London: John Wiley & Sons Ltd 527-70

Bennion H, Fluin J, Simpson GL (2004) Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. J Appl Ecol 41:124-138

Bernes C (1991) Acidification and liming of Swedish freshwaters. Schmidts Boktryckeri AB, Helsingborg

Bigler C, Heiri O, Krskova R, Lotter AF, Sturm M (2006) Distribution of diatoms, chironomids and cladocera in surface sediments of thirty mountain lakes in south-eastern Switzerland. Aquatic Sciences 68:154-171

Bindler R, Korsman T, Renberg I, Högberg P (2002) Pre-industrial atmospheric pollution: Was it important for the pH of acid-sensitive Swedish lakes? Ambio 31:460-465

Bishop KH, Laudon H, Hruška J, Kram P, Köhler S, Löfgren S (2001) Does acidification policy follow research in northern Sweden? The case of natural acidity during the 1990´s. Water Air Soil Pollut 130:1415-1420

Bos DG, Cumming BF (2003) Sedimentary cladoceran remains and their relationship to nutrients and other limnological variables in 53 lakes from British Columbia, Canada. Can J Fish Aquat Sci 60:1177-1189

Brännvall M-L, Bindler R, Emteryd O, Renberg I (2001) Four thousand years of atmospheric lead pollution in northern Europe: a summary from Swedish lake sediments. J Paleolimnol 25:421-435
Ek A, Korsman T (2001) A paleolimnological assessment of the effects of post-1970 reductions of sulfur deposition in Sweden. Can J Fish Aquat Sci 58:1692-1700
Ek A, Renberg I (2001) Heavy metal pollution and lake acidity changes caused by one thousand years of copper mining at Falun, central Sweden. J Paleolimnol 26:89-107
Erlandsson M, Fölster J, Laudon H, Weyhenmeyer GA, Bishop K (2008) Natural variability in lake pH on seasonal, interannual and decadal time scales: implications for assessment of human impact. Environ Sci Technol 42:5594-5599
European Union (2000) Directive 2000/60/EC of the European Parliament and the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L327:1-72
Glew JR, Smol JP, Last WM (2001) Sediment core collection and extrusion. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments Volume 1 Basin analysis, coring and chronological techniques. Kluwer Academic Publishers, Dordrecht 73-105.
Guhrén M, Rosén P, Korsman T, Renberg I (2003) Tidigare pH i referenssjöar i Sverige. Department of Ecology and Environmental Science, Umeå University, Umeå
Gählman V, Bigler C, Renberg I (2009) Kiselalger som miljöindikatorer i små vattendrag. Miljötillståndet i bäckar i Västerbotten år 2007 enligt ananlys av epilitiska kiselalger. Länsstyrelsens tryckeri, Västerbotten
Heiri O, Lotter AF (2001) Effect of low count sums on quantitative environmental reconstructions: an example using subfossil chironomids. J Paleolimnol 26:343-350
Henrikson L, Brodin YW (1995) Liming of acidified surface waters. Springer-Verlag, Berlin/Heidelberg
Hill MO, Gauch HG (1980) Detrended correspondence analysis: An improved ordination technique. Vegetatio 42:47-58
Ivarsson H, Jansson M (1995) Sources of acidity in running waters in central northern Sweden. Water Air Soil Pollut 84:233-251
Jeffries DS, Brydges TG, Dillon PJ, Keller W (2003) Monitoring the results of Canada/U.S.A acid rain control programs: some lake responses. Environ Monit Assess 88:3-19
Jensen KW, Snekvik E (1972) Low pH levels wipe out salmon and trout populations in southernmost Norway. Ambio 1:223–225
Johansson LS, Amsinck SL, Bjerring R, Jeppesen E (2005) Mid- to late-Holocene land-use change and lake development at Dallund Sø, Denmark: trophic structure inferred from cladoceran subfossils. Holocene 15:1143-1151
Johnson RK (2001) Defining reference condition and setting class boundaries in ecological monitoring and assessment. Department of Environmental Assessment, Swedish University of Agricultural Sciences, Uppsala
Juggins S (2005) C2 data analysis ver. 1.4.3 University of Newcastle
Juggins S, ter Braak CJF (1997) CALIBRATE a computer program for species environmental calibration by [weighted-averaging] partial least squares regression (0.81). University of Newcastle, Newcastle
Korsman T (1999) Temporal and spatial trends of lake acidity in northern Sweden. J Paleolimnol 22:1-15
Korsman T, Birks HJB (1996) Diatom-based water chemistry reconstructions from northern Sweden: a comparison of reconstruction techniques. J Paleolimnol 15:65-77
Korsman T, Renberg I, Andersen JH (1994) A palaeolimnological test of the influence of Norway spruce (Picea abies) immigration on lake-water acidity. Holocene 4:132-140
Krammer K, Lange-Bertalot H (1986-1991) Bacillariophyceae vol. 2(1–4). Gustav Fischer Verlag, Stuttgart/Jena

Kvaeven B, Ulstein MJ, Skjelkvåle BL, Raddum GG, Hovind H (2001) ICP Waters - An international programme for surface water monitoring. Water Air Soil Pollut 130:775-780

Larocque I, Hall RI, Grahn E (2001) Chironomids as indicators of climate change: a 100-lake training set from a subarctic region of northern Sweden (Lapland). J Paleolimnol 26:307-322

Laudon H, Köhler S, Bishop KH (1999) Natural acidity or anthropogenic acidification in the spring flood of northern Sweden? Sci Total Environ 234:63-73

Moldan F, Wright RF, Löfgren S, Forsius M, Ruoho-Airola T, Skjelkvåle BL (2001) Long-term changes in acidification and recovery at nine calibrated catchments in Norway, Sweden and Finland. Hydrology and Earth System Sciences 5:339-349

Monteith DT, Evans CD (2005) The United Kingdom Acid Waters Monitoring Network: a review of the first 15 years and introduction to the special issue. Environ Pollut 137:3-13

Moore PD, Webb JA, Collins ME (1991) Pollen Analysis. Blackwell Scientific Publications, Oxford

Odén S (1967) Nederbördens försurning. Dagens nyheter, 24 oktober 1967, Stockholm

Owen R, Duncan W, Pollard P (2002) Definition and establishment of reference conditions. Scottish Environment Protection Agency, Aberdeen

Overpeck JT, Webb T, Prentice IC (1985) Quantitative interpretation of fossil pollen spectra - dissimilarity coefficients and the method of modern analogs. Quat Res 23:87-108

Pearson K (1901) On lines and planes of closest fit to systems of points in space. Philosophical Magazine 2:559-572

Persson G, Ekström C (2001) Djurplankton före och efter kalkning av sjöar inom Integrerad KalkningsEffektUppföljning. Environmental Assessment, Swedish University of Agricultural Sciences, Uppsala

Persson G, Wilander A (2002) Allmän vattenkemi före och efter kalkning av sjöar inom Integrerad KalkningsEffektUppföljning. Environmental Assessment, Swedish University of Agricultural Sciences, Uppsala

Reizenstein M (2002) Fiskfaunans utveckling under 1900-talet i sjöar inom Integrerad KalkningsEffektUppföljning. Environmental Assessment, Swedish University of Agricultural Sciences, Uppsala

Renberg I (1990) A procedure for preparing large sets of diatom slides from sediment cores. J Paleolimnol 4:87-90

Renberg I, Hansson H (1993) A pump freeze-corer for recent sediments. Limnol Oceanogr 38:1317-1320

Renberg I, Hultberg H (1992) A paleolimnological assessment of acidification and liming effects on diatom assemblages in a Swedish lake. Can J Fish Aquat Sci 49:65-72

Renberg I, Hansson H (2008) The HTH sediment corer. J Paleolimnol 40:655-659

Renberg I, Korsman T, Birks HJB (1993a) Prehistoric increases in the pH of acid-sensitive Swedish lakes caused by land-use changes. Nature 362:824-827

Renberg I, Korsman T, Anderson NJ (1993b) A temporal perspective of lake acidification in Sweden. Ambio 22:264-271

Renberg I, Brännvall ML, Bindler R, Emteryd O (2000) Atmospheric lead pollution history during four millennia (2000 BC to 2000 AD) in Sweden. Ambio 29:150-156

Rosén P (2005) Total organic carbon (TOC) of lake water during the Holocene inferred from lake sediments and near-infrared spectroscopy (NIRS) in eight lakes from northern Sweden. Biogeochemistry 76:503-516

Rosén P, Persson P (2006) Fourier-transform infrared spectroscopy (FTIRS), a new method to infer past changes in tree-line position and TOC using lake sediment. J Paleolimnol 35:913-923

Sandøy S, Langåker RM (2001) Atlantic salmon and acidification in southern Norway: A disaster in the 20th century, but a hope for the future? Water Air Soil Pollut 130:1343-1348

Skjelkvåle BL, Mannio J, Wilander A, Andersen T (2001) Recovery from acidification of lakes in Finland, Norway and Sweden 1990-1999. Hydrol Earth Syst Sci 5:327-337

Skjelkvåle BL, Stoddard JL, Jeffries DS, Tørseth K, Høgåsen T, Bowman J, Mannio J, Monteith DT, Mosello R, Rogora M, Rzychon D, Veselý J, Wieting J, Wilander A, Worsztynowicz A (2005) Regional scale evidence for improvments in surface water chemistry 1990-2001. Environ Pollut 137:165-176

Smol JP (2008) Pollution of lakes and rivers: a paleoenvironmental perspective. Blackwell publishing, Singapore

Smol JP, Birks HJB, Last WM (2001) Tracking environmental change using lake sediments: Terrestrial, algal, and siliceous indicators. Kluwer Academic Publisher, Dordrecht

Stevenson AC, Juggins S, Birks HJB, Anderson DS, Anderson NJ, Battarbee RW, Berge F, Davis RB, Flower RJ, Haworth EY, Jones VJ, Kingston JC, Kreiser AM, Line JM, Munro MAR, Renberg I (1991) The Surface Waters Acidification Project paleolimnology programme: Modern diatom/lake-water chemistry data-set. ENSIS Publishing, London

Stoermer EF, Smol JP (1999) The Diatoms: Applications for the environmental and earth sciences. Cambridge University Press, Cambridge

Swedish Environmental Protection Agency (2002) Kalkning av sjöar och vattendrag. Naturvårdsverkets förlag, Stockholm

Swedish Environmental Protection Agency (2007) Status, potential och kvalitetskrav för sjöar, vattendrag, kustvatten och vatten i övergångszon : en handbok om hur kvalitetskrav i ytvattenförekomster kan bestämmas och följas upp : handbok för tillämpning av 4 kapitlet 1-4 och 7 §§ förordningen (2004:660) om förvaltning av kvaliteten på vattenmiljön samt Naturvårdsverkets föreskrifter (NFS 2008:1) och allmänna råd om klassificering och miljökvalitetsnormer avseende ytvatten, Stockholm

Swedish Environmental Protection Agency (2009). Kalkning av sjöar och vattendrag. Retrieved February 06, 2009, from http://www.naturvardsverket.se (2007-08-08)

Sweetman JN, Smol JP (2006) Patterns in the distribution of cladocerans (Crustacea : Branchiopoda) in lakes across a north-south transect in Alaska, USA. Hydrobiologia 553:277-291

ter Braak CJF, Šmilauer P (2002) CANOCO reference manual and CanoDraw for Windows Users´s guide: Software for canonical community ordination (version 4.5). Microcomputer Power, Ithaca

Törnqvist A. (2008) Bergsbruk och aristokrati. Järnhantering, jordbruk och landskap i Norbergs Bergslag. Meddelande 138. Kulturgeografiska institutionen, Stockholm universitet

Wallin M, Wiederholm T, Johnson RK (2003) Guidance on establishing reference conditions and ecological status class boundaries for inland surface waters, Produced by Working Group 2.3 - Reference conditions for inland surface waters (REFCOND)

Washington HG (1984) Diversity, biotic and similarity indices. A review with special relevance to aquatic ecosystems. Water Res 18:653-694

Wik M, Renberg I (1996) Environmental records of carbonaceous fly-ash particles from fossil-fuel combustion. J Paleolimnol 15:193-206