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

Matilda Norberg
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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
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List of papers

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


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


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¹ In 2007 my surname was changed from Guhrén to Norberg
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 (Kvaaven 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 µeq 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 (²⁰⁶Pb/²⁰⁷Pb) – 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 indicators 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.

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Populärvetenskaplig sammanfattning


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 referensställande i sjöar som påverkats av människan är.

Jag har också 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 jordäcke 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 spelas 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.


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乡村振兴linewidth:2px]ortic, alltid om 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.

Tack


Christian Bigler har under stor del av min doktorandtid varit min biträdehandledare. Tålmodigt har han funnits till hands och hjälp till med allt från identifiering av triga 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.

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.


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, glimmer, djup, nytänkande och kärlek i livet. Ni är viktigast av allt. Tack för att ni finns.

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