Improved reference values for phosphorus in Swedish agricultural lakes

Lake sediment records of historical concentrations in Sweden and near-by countries

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Improved reference values for phosphorus in Swedish agricultural lakes - Lake sediment records of historical concentrations in Sweden and near-by countries

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Summary

This report reviews the paleolimnological methods that can be used to reconstruct past lake-water total phosphorus (TotP) in Swedish agricultural lakes, including available data sets and data set management techniques. It also summarizes the results of five studies of eleven Swedish lakes and results from similar studies in near-by countries.

The results highlight the complexity of the long-term effects of human land use. Firstly, the onset of agriculturally driven TotP increase varies from the medieval period to the 20th century, with some lakes apparently unaffected (with respect to TotP at least) by agriculture in their catchments. Secondly, the impact of some preindustrial agriculture was significant. If we assume a reference condition with no human impact, some lakes were likely at a moderate or worse ecological status already before 1850 CE due to preindustrial agriculture. However, the number of Swedish lakes with TotP-reconstructions is low compared to some near-by countries and these results are anecdotal.

We suggest that further studies are carried out, using short sediment cores (i.e. ~50 cm) on a larger number of lakes. While short cores would only cover the last few hundred years, they would provide more data on preindustrial TotP levels and the development through the industrial period which could be the basis of more realistic reference values for phosphorous in an agricultural landscape.

Keywords: Lake sediment, Total phosphorus, Diatoms, Reference values, Background, Transfer functions

Contents

1. Introduction

According to the Water Framework Directive (WFD) all waterbodies should be classified according to ecological status, defined as a deviation from a reference state representing a non-disturbed state (EC 2000). This is specified in the Guidance document REFCOND as a state with only very minor disturbances from human pressures on the ecosystem (EC 2003). The definition of the reference state should include hydromorphological, physiochemical and biological quality elements. Water bodies should be divided into types according to e.g. ecoregion, size and geology. For each type, a number of reference sites should be designated for defining the reference state for all quality elements. Alternatively, predictive modelling can be used for setting site specific reference conditions. In regions where minimally disturbed sites are not found, a historical state defined by historical data or paleolimnological reconstructions can be used. For example, in a region dominated by agriculture, a state before intensive agriculture was suggested as the reference state in the REF-COND document. For the biological quality elements, the classification systems were intercalibrated between member states within a number of regions (EC 2000). For physicochemical quality elements, however, no such intercalibration was performed. An evaluation of the classification of nutrients indicated large differences between good/moderate boundaries (Phillips et al. 2015). The results indicates that there also were differences between how the reference conditions were defined and how “minimally disturbed” and “preintensive agriculture” were interpreted in the national implementation of the WFD.

A comparison of the quality standard for nutrients in the Nordic countries showed that the classification of total phosphorus (TotP) for inland waters in the forest dominated landscape was rather similar, but in the agricultural landscape, there were considerable differences on how reference values were set in agricultural dominated rivers (Skarbøvik et al. 2020).

The Swedish quality criteria for TotP in lakes includes site specific reference values calculated with water color and altitude by a multiple linear regression model on data from reference lakes. The reference lakes were selected from a lake survey with a reference filter allowing <10 % agricultural land, but with a strong dominance of only forest and mire in the catchment. This means that the reference state for lakes in an agricultural landscape are set by forest lakes, despite the fact that the forest lakes occur mainly on nutrient poor granitoid till soils, while agriculture is practiced mainly on naturally nutrient rich clay morains or sedimentary soils (Fölster et al. 2018, HaV 2018). For rivers, a similar regression model is used for the reference value of TotP, but for rivers with >10 % agricultural land in the catchment, a modelled back-ground value is used. This background value represents root zone leakage from an unfertilized and unharvested fallow taking into account the local soil properties, slope and region. Net retention from the root zone to river is represented by a factor 0.5 (HaV 2018). These two reference states are inconsistent and both more conservative than the preindustrial agriculture suggested in the REFCOND document. In many cases, this means that good ecological status may be impossible to reach with agriculture performed in the catchments.

Modelled results show that identifying a preindustrial state is challenging. Even before the use of industrial fertilizers, ditching of wetland to gain agricultural land and suboptimal handling of manure might have elevated nutrient leaching to the same level as present (Hoffmann et al. 2000, Christensen et al. 2021).

Paleolimnology gives an opportunity to independently reconstruct past phosphorus concentrations. Where even the longest monitoring series covers decades to perhaps a century, the sediment represents a natural archive which in most Swedish lakes stretches back to the retreat of the latest ice sheet. Given a continuous sedimentation and the presence of well-preserved diatom (a single-celled algae) remains, it is possible to reconstruct lake-water TotP. Albeit with some environmental and methodological constraints (see chapter 2). The aim of this study is to investigate the extent of paleolimnological reconstruction of TotP in Sweden and near-by countries to date as well as the potential for using paleolimnology to inform future reference conditions for lakes in the agricultural landscape.

2. Paleolimnological methods

Diatoms are single-celled algae present in almost all aquatic environments and their unique silica-enforced cell wall is generally well preserved in lake sediments. Using the characteristic shape, size and distribution of pores, diatom fossils can be identified to taxa which carry environmental information (Battarbee et al., 2001). The most common method used to infer past environments involves the construction of a "training set" consisting of diatom taxa compositions of surface-sediment samples paired with measurements of lake-water variables. Using a weighted averaging (WA) regression (or WA partial least squares regression; WA-PLS) each training set taxa is assigned an optimum of the environmental variable of choice. These optima can then be used to calibrate the past environment for any sample with known diatom composition, given that a set of assumptions are true. Two important assumptions are that the variable of choice is the main determinant of taxa composition and that the same taxa are present in both training set and the sample to be calibrated (see Juggins & Birks 2012 for more details).

Historically, the focus in Sweden has been on reconstructing the development of pH, both the long-term natural development and the human impacts associated with land use and industrial acid deposition (Figure 1; Renberg et al., 1993). These reconstructions most often used a dataset containing samples from 178 lakes from the British isles and Scandinavia (Birks et al., 1990) and are generally robust because pH is one of the most important variables controlling the diatom composition (Battarbee et al., 2001).

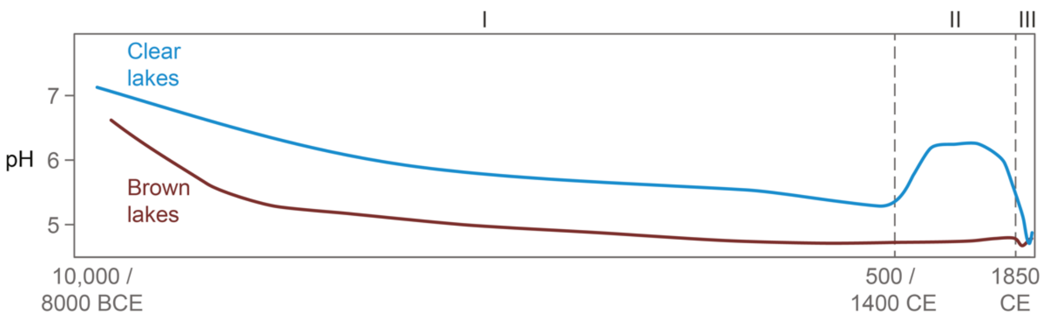

Figure 1. Conceptual development of pH since the last glaciation (adapted from data published in Myrstener et al., 2021). Roman numerals represent developmental phases: I Background, II Preindustrial human impact (i.e. agriculture); III Industrial human impacts.

Reconstructions of phosphorous (most often total phosphorus; TotP) are also common internationally (Bennion et al., 2011 and references therein) but so far have seen only a few applications in Sweden (Table 1). The most common method of TP reconstruction is based on the large Northwestern European (NW-EU) training set with 152 lakes from the British isles and Scandinavia and a WA-PLS model (Bennion et al., 1996; r^2 0.91, RMSEP 1.62 µg P L^{-1}).

It's important to note that while TotP is the main variable driving diatom productivity (Battarbee et al., 2001), large changes in pH (or other confounding variables) can introduce a significant bias in a model (Juggins, 2013). For this reason, TotP training sets are usually constructed from and applied to mostly alkaline lakes where the stable pH allows for robust reconstructions of TotP. Other potential sources of model bias include secondary gradients and noise from a large training set (Juggins & Birks, 2012) or a systematic over-estimation of values at the lower end of a training set gradient (Bradshaw & Anderson, 2001; Hübener et al., 2008).

Table 1. Training sets and models for TP reconstructions applied in Sweden and other countries.

Country/state	Training set	Used in lake
Sweden	Sweden (Bradshaw & Anderson, 2001)	Ekoln, Mälaren (Bradshaw & Anderson, 2001) Södra Björkfjrd., Mälaren (Renberg et al., 2001)
	NW-EU*	Milsbosjön (Rydberg, Bigler, Wallin, et al., 2006) Florsjön, Östersjön (Bigler et al., 2007) Dalslands kanal (Rydberg, Bigler & Renberg, 2006)
Finland	Finland-1 (Kauppila et al., 2002)	Finland (Kauppila et al., 2002) Kaljasjärvi (Kauppila & Valpola, 2003) Hampträsk (Luoto et al., 2009)
	Finland-2 (Miettinen, 2003)	6 lakes in Karelia (Miettinen et al., 2005)
	Finland-3 (Tammelin et al., 2017)	Finland (Tammelin et al., 2017)
	Finland 1–3	(Tammelin et al., 2019)
Denmark	Danmark*	Dallund sø (Bradshaw et al., 2005)
	NW-EU*	Lake Søbygård (Bennion et al., 1996) 21 lakes (Bjerring et al., 2008)
	Denmark/NW-EU?*	(Amsinck et al., 2003)
Norway	Modified NW-EU?*	Mjøsa (Hobæk et al., 2012)
Germany	EDDI+Moving window (Hübener et al., 2008)	4 lakes (Hübener et al., 2008) 14 lakes in northern Germany (Hübener et al., 2015)
	EDDI+Mecklenburg-Vorpommern lakes	Sacrower See (Kirilova et al., 2009)
Great Britain	NW-EU*	Scotland (Bennion et al., 2004)
Switzerland	Switzerland	68 lakes (Lotter et al., 1998)
Minnesota	Minnesota*	55 lakes (Heiskary & Wilson, 2008)

* model references: NW-EU (Bennion et al., 1996), Denmark (only plankton; Bradshaw et al., 2002), NW-EU? (Hobæk et al., 2012), EDDI+Mecklenburg-Vorpommern lakes (Adler & Hübener, 2007), Minnesota (Heiskary & Swain, 2002).

Bradshaw & Anderson (2001) present a Swedish model based on 43 lakes and a WA model (inverse deshrinking and tolerance down-weighing; r^2 0.79, RMSEP 1.9 µg P L^{-1}, max bias 3.7 µg P L^{-1}) which they report produces less bias for low TotP, but instead a larger bias for high TotP (>80 µg P L^{-1}), compared to the NW-EU training set. Importantly, they report large differences in the optima of certain diatom taxa compared to the NW-EU training set, which likely partially explains the differences in predicted values. Similar local training sets have been developed for other countries (e.g. Bradshaw et al., 2005; Tammelin et al., 2019) and the Swedish training set could be valuable for future TotP reconstructions of Swedish lakes, especially for the presumably oligo- to mesotrophic background or preindustrial conditions.

Other approaches to limit model bias include selecting subsets of sites or taxa from a large training set. Hübener et al. (2008) present a ”moving window” approach which uses detrended correspondence analysis to identify a subset of nearest neighbour lakes (40–160) from the training set for each sample. This subset is then used as the training set for that specific sample. Juggins et al. (2015) and Köster et al. (2004) present methods to prune non-informative taxa from the training set to reduce model noise and bias. However, none of these methods have so far achieved wider application.

2.1. Supporting or alternative parameters

Diatoms-based methods are the only widely used method of quantitative TotP reconstructions. Other organisms or paleolimnological proxies can be used as supporting information or even as alternatives to diatoms to study lake productivity and ecosystem development. Cladocera are partially preserved in sediments and Davidson et al. (2011) show strong correlations between Cladocera composition and macrophyte cover in a set of Danish lakes. This could be useful supporting information to a diatom-TotP reconstruction or used in itself to inform reference targets for macrophytes in lakes. However, Cladocera composition is also influenced by pH, conductivity and planktivorous fish (Bjerring et al., 2009) and must be interpreted carefully.

3. Paleolimnological TotP reconstructions

Lake sediment profiles from previously glaciated landscapes typically cover the entire period since deglaciation (~8,000–12,000 years in south-central Sweden), or the time since land uplift isolated the lake from the sea (a still ongoing process). A complete profile thus gives continuous data on the lake development on time-scales orders of magnitude beyond any monitoring series. To study the long-term development of lake trophic status in particular, diatom TP reconstructions are typically combined with pollen profiles which allows for the identification of background states as well as the magnitude of subsequent human land use.
A study of Nedre Milsbosjön, in Dalarna county, showed that background TotP concentrations were ~30 µg P L^{-1} (Rydberg et al. 2006). Following the establishment of agriculture at ~500 CE (indicated by pollen data) TotP becomes more varied, fluctu-ating between ~25–50 µg P L^{-1}. After ~1950 CE concentrations increased sharply to ~200 µg P L^{-1}, likely associated with the establishment of industrial agriculture with tilling and artificial fertilizer. Concentrations have decreased more recently to ~100 µg P L^{-1}. A study of two lakes, Florsjön and Östersjön, showed background concentrations of ~20 µg P L^{-1} (Bigler et al. 2007), but here peak concentrations of 40–60 µg P L^{-1} occur between 1500 and 1800 CE. This is likely an effect of linen production at the lakes centered round the 18th century and an important reminder of the varied history on human land use. It is important to note that the TotP reconstruction for the most recent samples of these sites is slightly different than measured values, which indicates some bias for the absolute values of the reconstruction.

More studies highlight this long, complex history of human impact on lake trophic status using indirect methods rather that direct TotP-inference. Håkansson & Regnéll (1993) studied Bussjösjön, a shallow, alkaline lake in Skåne where the pollen com-position indicate early forest clearance in favor of pasture land already at ~750 BCE, a transition to cereal cultivation from ~650 CE and industrial agriculture during the 20th century. The background diatom taxa suggest moderately eutrophic conditions. Each step of intensified land use is then accompanied by progressively more nutrient demanding diatom taxa ending in the present day eutrophic to hypereutrophic condition.

The long history of human land-use and its effects on lake trophic status is seen in other countries in Europe. A study of 14 alkaline lakes in the northern German low-lands (Hübener et al., 2015) indicates a long but varied history of human landuse is the region where pollen and diatom-inferred TotP indicate that the lakes deviate from background conditions at different times: ~1300 CE for four lakes, ~1600 CE for two lakes, >1650 two lakes, ~1850 three lakes and one lake with background levels of TotP still today. Tammelin el al. (2019) studied 3 lakes in central Finland with unusually high background TotP concentrations (~40-60 µg L^{-1}), which the authors attribute to the unusually fine-grained till in the area. Two of the three lakes show increasing TotP from ~1600 CE, coinciding with the time when historical documents show the area was settled.

The long-term development of phosphorous and its interaction with human land-use in oligotrophic lakes has received less attention. However, some studies allow for at least some speculation. In Kassjön, a large lake in northern Sweden, Anderson et al. (1995) used the nature of the varved (annually laminated) sediment of the lake to calculate diatom deposition rates. Pollen data indicates land clearance and establishment of agriculture from late 13th century and while this is less dramatic than what is seen in many southern lakes, diatom accumulation rates and the appearance of more nutrient demanding diatom taxa indicates increased trophic status of the lake. Other studies show effects of less intensive land use (a combination of forest grazing, land clearance and small-scale crop cultivation) on oligotrophic lakes in the form of increasing pH (Guhrén et al., 2007; Renberg, Korsman & Birks, 1993) and decreasing lake-water TOC (and thus color; Meyer-Jacob et al., 2015; Myrstener et al., 2019, 2021). The processes that drive the alkalization and reductions in lake-water TOC (soil disturbance, erosion and depletion of organic soil horizons) likely also affect nutrient export and change ecosystem function, but if this has measurable long-term effects on lake-water TotP is unknown. Recent limnological studies have shown extended oligotrophication in the northern hemisphere, with climate change and recovery from acidification as possible explanations (Huser et al 2018). Paleolimnological studies on non-eutrophied oligotrophic lakes covering prehistoric warming periods could help to disentangle the causes of the oligotrophication. However, as discussed in chapter two, the existing diatom TotP training sets are not designed for oligotrophic lakes and the presence of confounding variables (e.g. pH) would complicate reconstructions.

3.1. Short cores reveal recent changes

A different approach to the study of lake trophic history is to use more but shorter cores. A surface core typically covers only a few hundred years, but they are faster and cheaper to sample and analyze and thus are valuable to provide data on more lakes. Renberg et al. (2001) present data from a short core from Södra Björkfjärden (a bay in Mälaren) where TotP concentrations were stable at ~40 µg P L^{-1} before ~1850 CE, rose to 70 µg P L^{-1} after 1950 and then decreased to ~50–60 µg P L^{-1} in the top samples. However, the values from contemporary surface water monitoring are 20–30 µg P L^{-1} lower than the modelled values since the late 1960s so there's an apparent bias in the model. A study of six oligotrophic lakes in Dalsland show a uniformly low TotP of 4–8 µg P L^{-1} during the 19th century (Rydberg, Bigler & Renberg, 2006). In two of the lakes TotP increases to 11 and 14 µg P L^{-1} during the 20th century, likely in response to sewage emissions and possibly the establishment of paper mills at the lakes. Here the 19th century concentrations likely represent background concentrations due the low impact of agriculture in the region even today.

These short-core studies are more common internationally. A metastudy on short cores (100–200 years) from 95 lakes in northern Europe (mainly British and Scandinavian lakes) show a distribution of TotP between 10–100 µg L^{-1} at ~1850 CE, with many oligo- and mesotrophic sites (Battarbee et al., 2011). Compared to the top samples representing the most recent decades, there is a noticeable loss of oligotrophic sites, an increase in eutrophic sites and the creation of several hypereutrophic sites. The authors also note that when the lakes are sorted into types according to the WFD, the standard deviation of preindustrial TotP within each type is large and thus recommend individual reference conditions. Another study with TotP reconstructions from 17 Danish lakes (Amsinck et al., 2003) show surprisingly high TotP already at 1850 CE, including some hypereutrophic lakes, and the authors caution that some lakes may have been severely impacted already at this time. Nevertheless, the study shows marked eutrophication in many of the lakes with the generally highest TotP around 1950 CE. A study by Tammelin & Kauppila (2018) infer the position of when industrial agriculture started affecting the lakes using magnetic susceptibility in 48 lakes in central Finland. They show a large variability of predisturbance TotP (8–60 µg l^{-1}), however it is unknown if these samples represent background or just a lower impact stage. Compared to contemporary, conventional TotP measurements, the lakes with preindustrial TotP <35 µg l^{-1} are largely unchanged today while the lakes >35 µg l^{-1} show greater variability, but in general greater eutrophication. The preindustrial variability the authors attribute to natural soil grain-size differences and the variability in human impact between lakes they attribute to differences in the distribution of agriculture.

4. Discussion

The three long cores from Sweden (Table 2) all show a human-driven increase in TotP well before the onset of industrial agriculture. For Mälaren, its late isolation from the Baltic sea at some point 1100–1300 CE (Risberg et al., 2002) and the wide-spread agriculture in its catchment already at this time means that a background value is not definable. This long history of human impact on TotP concentrations is also seen in Denmark (Bradshaw et al., 2005), Finland (Tammelin et al., 2019), Germany (Hübener et al., 2015). However, many examples of lakes with agriculture but no increase in TotP exist (Hübener et al., 2015; Tammelin et al., 2019; Tammelin & Kauppila, 2018), highlighting the complexity of human-lake interactions.

Table 2. Overview of reconstructed and measured TotP for Swedish lakes. Green values are apparently unbiased reconstructions when compared to measured values (in gray) while red and blue values appear biased; high and low respectively. All ages are in years CE and TotP in $\mu g\ L^{-1}$.

Lake	Background TotP	Preindustrial TotP (year[7])	Max TotP (year[7])	Contemporary TP
Mälaren–Ekoln[1] basin	NA*	50–60	99 (~1966)	~50
Measured:			~90	~60
Mälaren–Södra Björkfjärden[2]	NA*	40	70 (~1950)	50–60
Measured:			30–40	20–30
Nedre Milsbosjön[3]	~30	25–50 (~500)	180 (~1990)	-
Measured:			~230	~125
Florsjön[4]	20	~35 (~1100)	50-60 (17–1900)	30–40
Measured:				25
Östersjön[4]	20	~55 (~1300)	40 (16–1800)	20
Measured:				~40
Stora Le[5]		4–5		~6
Foxen[5]		5–8		5–8
Västra Silen[5]		3–6		6–8
Lelången[5]		5–8		5–8
Laxsjön[5]		6		7-14
Råvarpen[5]		7		11
Finland				
Saarisjärvi[6]	~33	~58 (1500)		68
Porovesi[6]	~45	~65		~65

* Mälaren was only isolated from the Baltic sea in ~1300 CE and because agriculture was widespread in the catchment at this time a background value is undefinable.
[1](Bradshaw & Anderson, 2001), [2](Renberg et al., 2001), [3](Rydberg, Bigler, Wallin et al., 2006), [4](Bigler et al., 2007), [5](Rydberg, Bigler & Renberg, 2006), [6](Tammelin et al., 2019), [7](Hill et al. 1999).

It is not only the timing of when early human land-use started that varied, the magnitude of the TotP increase also varied (Table 2). Nedre Milsobosjön shows intermittent peaks in TotP following the establishment of agriculture at the lake, but on average the increase is only a few µg L^{-1}. In Florsjön on the other hand, TotP almost doubled and in Östersjön TotP almost tripled before the industrialization (compared to background values). Using the moderate/good status boundary of twice the background in the present Swedish legislation (HVMFS, 2018:17, this means Östersjön was already at moderate or worse status before the onset of industrial agriculture and Florsjön was teetering on the boundary. A similar comparison for the two Finnish lakes indicates that Porovesi has remained at good status throughout both preindustrial and industrial agriculture while Saarisjärvi was just barely good status during preindustrial agriculture but decreased to moderate or worse status during the 20th century (Tammelin et al., 2019).

Considering the variability in starting time and magnitude of human-driven TotP increase, a paleolimnological investigation of true background values in Swedish low-land lakes would be a significant undertaking. Moreover, setting a reference value at no human impact (i.e. background) for TotP would mean that many lakes were at moderate or close to moderate status already before the establishment of industrial agriculture. Here, a short core study would provide data on many more lakes than the more involved long-core studies. Additionally, the preindustrial agriculture used markedly less fertilizer and no mechanized ploughs and pre-1850 CE values would provide useful information on realistic reference values to the environmental management, as seen in many international studies (Amsinck et al., 2003; Battarbee et al., 2011; Heiskary & Wilson, 2008).

Furthermore, the apparent bias in some of the diatom-inferred TotP values compared to directly measured monitoring data should also be addressed to ensure as good quality data as possible. Given that the training sets used for TotP reconstructions are over 20 years old at the writing of this report, the number of lakes with several decades' worth of monitoring data have increased giving more good candidates for a preliminary study comparing measured TotP to the values predicted by the various training sets and models (Bennion et al., 1996; Bradshaw et al., 2002; Hübener et al., 2008). The development of new data management methods (Juggins et al., 2015; Köster et al., 2004) could also help improve model performance.

It's important to note that this discussion concerns lakes with agriculture today and cannot easily be applied to forest lakes due to differences in their land-use histories. The geological factors which determine where agriculture is located (e.g. grainsize, nutrient availability and climate) don't change markedly with time. Furthermore, before the 20th century, agriculture and related land-uses was much more wide spread in the landscape and included extensive forest grazing, mire haymaking, coppicing and charcoal making (Lagerås, 2007; Myrstener, Ninnes et al., 2021). Thus lakes with agriculture today likely had agriculture during the 19th century too while lakes that today have little or no agriculture in their catchments (specifically forest lakes) may well have had agriculture historically. Therefore, the preindustrial (i.e. pre 1850 CE) period for agricultural lakes would be a useful comparison for what levels are achievable with a continued presence of agriculture. For the forest lakes on the other hand, if the now abandoned preindustrial agriculture and land use had a measurable effect on TotP, a reference state of pre 1850 CE would represent too high levels of TotP and could allow other activities such as sewage to affect lakes without lowering their status. For these lakes, paleolimnological TotP reconstructions could give insight into the long-term effects of human land use and link this to the observed contemporary oligotrophication (Huser et al., 2018) but methodological problems have so far prevented such studies.

We suggest that an extensive paleolimnological study is undertaken in Swedish lakes in the agricultural landscape with core depths giving pre 1850 CE values of TotP reconstructions. The results should be evaluated in the context of land use history and historical changes of the hydrography to show if this historical state can be used to support a discussion to find a reference state for lakes in the agricultural landscape. Thus giving realistic possibilities to reach good ecological status with sustained food production in the catchment as well as a better acceptance by the stakeholders.

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