Hydrobiologia (2009) 625:157–172
DOI 10.1007/s10750-009-9705-0

PRIMARY RESEARCH PAPER

Effects of hypolimnetic oxygenation on water quality: results from five Danish lakes

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Received: 29 September 2008 / Revised: 23 December 2008 / Accepted: 2 January 2009 / Published online: 19 January 2009

Abstract Stratified eutrophic lakes often suffer from hypolimnetic oxygen depletion during summer. This may lead to low redox conditions and accumulation of phosphate and ammonia in the hypolimnion. Hypolimnetic oxygenation has been used as a lake management strategy to improve the water quality in five eutrophic dimictic Danish lakes where oxygenation was conducted for 4–20 years. In one lake, the hypolimnetic oxygen concentration clearly improved by oxygenation, whereas the other four lakes still exhibited low mean summer levels (<2.2 mg O_2 l^{-1}). Oxygenation generally increased the hypolimnetic water temperature by 0.5–2°C, but in one lake it increased by 4–6°C. In all lakes, oxygenation significantly reduced the hypolimnetic concentrations of phosphorus and ammonia during stratification. The accumulation of phosphorus and ammonia typically decreased by 40–88%. In two lakes oxygenation was stopped for 1–2 years and here hypolimnion concentrations of both phosphorus and ammonia increased again. Surface water quality only improved in one lake, but was likely also influenced by simultaneously occurring changes in external nutrient loading. Overall, it is concluded that hypolimnetic oxygenation reduces the hypolimnetic accumulation of phosphorus and ammonia and may prevent anoxia in the deeper parts of the lake. However, long-term oxygenation is required and it is uncertain whether the overall lake water quality can be improved by oxygenation. Reduction of the external nutrient loading is still essential to improve lake water quality.

Keywords Oxygen · Lake restoration · Anoxic · Oxygenation · Nutrient accumulation · Lake management

Handling editor: Luigi Naselli-Flores

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Introduction

In deep eutrophic lakes partial or complete hypolimnetic anoxia is often seen during summer stratification. This is due to decomposition of organic matter and lack of exchange with the upper water layer (epilimnion). One of the main problems caused by prolonged periods with anoxic sediments is phosphate release due to the redox-dependent release from iron hydroxides (Mortimer, 1941) and bacteria (Gächter, 1987). If phosphorus enters into the productive surface water, for instance during the autumn overturn, the released phosphate may stimulate algal production and deteriorate the overall lake water quality in autumn and spring. Hypolimnetic anoxia may also cause accumulation of various reduced compounds such as ammonia, sulphide, manganese and iron (Höhener & Gächter, 1994; Holmer & Storkholm, 2001), which may potentially have toxic effects on the biota and intensify eutrophication (Wang & Chapman, 1999; Camargo & Alonso, 2006). Oxygen depletion in the hypolimnion can also have direct negative effects on benthic invertebrates and fish. Several studies have described decreased densities and diversity of the benthos as less oxygen is dissolved in the water column (Jonasson, 1984; Doke et al., 1995; Dinsmore & Prepas, 1997; Devine & Vanni, 2002). Likewise, the loss of oxygenated, cold-water habitats can be critical for some fish species (Aku & Tonn, 1999), just as their natural reproduction may be reduced because of suffocation of eggs developing on the sediment (Müller & Stadelmann, 2004).

Hypolimnetic oxygenation, defined as the use of pure oxygen to aerate the hypolimnion rather than air as used in hypolimnetic aeration, has been implemented worldwide in a number of deep productive lakes and reservoirs suffering from the negative impacts of anoxia (Beutel & Horne, 1999; Singleton & Little, 2006). In some lakes oxygenation clearly improved the hypolimnetic oxygen conditions (Matinvesi, 1996; Gemza, 1997; Prepas & Burke, 1997; Gächter & Wehrli, 1998; Beutel & Horne, 1999), while others still experienced extended periods with an anoxic or close to anoxic hypolimnion (Klumb et al., 2004; Müller & Stadelmann, 2004). Likewise, oxygenation is reported to have had a significant effect on the nutrient turnover and to have reduced the hypolimnetic accumulation of ammonia and phosphorus (Gemza, 1997; Prepas & Burke, 1997). However, in some cases the internal phosphorus cycling is not affected by the improved oxic conditions (Gächter & Wehrli, 1998). Slightly improved oxygen conditions may render the metalimnion or hypolimnion a low-oxygen refuge for large-bodied herbivorous zooplankton from fish predation and thereby indirectly improve the water clarity by excessive grazing (Gemza, 1997; Klumb et al., 2004). Other positive effects observed from oxygenation are the expansion of living space for fish and benthic invertebrates and prevention of fish kills by upwelling anoxic hypolimnetic water (Müller & Stadelmann, 2004).

Most reports on the effects of oxygenation on the water quality and biological communities of the lakes are, however, based on single-lake investigations. Only few papers exist that review general overall trends from multiple lakes (Beutel & Horne, 1999), making it difficult to draw more general conclusions regarding the use of hypolimnetic oxygenation as a lake restoration tool. Also the seasonal variations in dissolved oxygen, temperature and nutrient dynamics several years before and during the treatment have only rarely been described (Dinsmore & Prepas, 1997), and a more dynamic description of the processes is therefore not feasible.

The main objective of this article is to present the overall results obtained from hypolimnetic oxygenation projects in Denmark. The analysis is based on pre-oxygenation and during oxygenation data from five lakes oxygenated for 4–20 years. We focus on identifying general seasonal patterns by analysing effects on central chemical variables and evaluating the potential for long-term permanent improvements of water quality.

Methods

Description of the lakes and the hypolimnetic oxygenation

Hypolimnetic oxygenation has been applied to five Danish lakes with the aim to improve lake water quality. The size of the lakes varies from 0.08 to 9.4 km^2 and the hydraulic retention time from 0.6 to 12 years. Mean depth ranges from 5 to 14 m, and only two lakes have a maximum depth above 12 m

Table 1 Morphometry for the five Danish lakes where hypolimnetic oxygenation has been applied

	Area (km^2)	Volume ($\times 10^6$ m^3)	Max. depth (m)	Mean depth (m)	Hydraulic retention time (year)
Lake Hald	3.4	45	31	13.1	1.3
Lake Vedsted	0.08	0.4	11.9	5	2.7
Lake Viborg Nørresø	1.2	8.6	12	7	0.6–0.9
Lake Torup	0.2	0.8	9.5	3.92	2.6
Lake Fure	9.4	122.2	37.7	13.5	12

(Table 1). All the lakes have been exposed to anthropogenic eutrophication and have suffered from anoxia or experienced relatively long periods of critically low concentrations of oxygen near the bottom during stratification. In some of the lakes massive blooms of cyanobacteria occurred in summer. The sediment of most Danish lakes is rich in organic matter and iron concentrations are relatively high (Søndergaard et al., 1996).

All five lakes were initially oxygenated using the same methodology. One lake was oxygenated for more than 20 years, two for more than 10 years, and the last two for 4–5 years (Table 2). The oxygenation device consisted of an onshore facility including a liquid oxygen storage tank and evaporators that transformed the liquid oxygen to gas. The gas was then transported to the deepest areas of the lake through pipes or tubes and released as small bubbles from different types of diffuser systems. As the small bubbles rise through the water column they are dissolved in the hypolimnion, thereby oxygenating waters above the pipes. During most years, oxygenation was initiated in May or June when the summer stratification was established, and lasted until September–October. In Lake Torup a shift to a land-based oxygenation system was made after 2 years (see below).

Lake Hald

The first of the oxygenation projects was initiated in summer 1985 in Lake Hald in Central Jutland and the lake has been oxygenated every summer since then, excepting 1998 and 2006 (Table 2). We divided the treatment period into: (1) 1985–1994 when oxygen was supplied by eight diffusers to the four deepest areas in the lake and with a total dosing of 200–300 t O_2 y^{-1}, corresponding to a mean supply of 2.1–3.2 t O_2 d^{-1} and (2) 1995–2004 when oxygen was supplied to the same areas by four diffusers with a gradually reduced dosing from 200–300 t O_2 y^{-1} to

Table 2 Annual oxygen demand, annual oxygen supply and years of hypolimnetic oxygenation during summer in five Danish lakes

	Years of oxygenation	Annual oxygen demand	Annual oxygen supply		
		Total (t)	Total (t)	($g\ m^{-2}$ hypolim. area)	($g\ m^{-3}$ hypolim. vol.)
Lake Hald	1985 to >2007 (1998, 2006)	~200–300	100–300	~77–231	~5–16
Lake Vedsted	1995–2007 (2002, 2003)	NA	7.2 (mean)	~222	~57
Lake Viborg Nørresø	1996 to >2007	NA	11–136	~17–209	~8–94
Lake Torup[a]	2002 to >2007	~7.1	5.4–9.6	~104–185	~57–101
Lake Fure[b]	2003 to >2007	~640–950	320–650	~72–146	~7–14

The annual oxygen demand was estimated before the oxygenation was initiated, from rates of daily oxygen consumption multiplied by the number of days with stratification. Years without oxygenation are given in parentheses. In several of the lakes it is still not decided when the treatment will be stopped. The estimate for the oxygen supply per hypolimnion area and volume is based on mean values for the depth of the thermocline during stratification

NA not available

[a] Different oxygenation methods in 2002–2003 and 2004–2007

[b] Removal of 200 t cyprinids 2003–2006, measured efficiency of the oxygenation: 93–95% (www.furesoeprojekt.dk)

approximately 100 t O_2 y^{-1}. In 2005, only one diffuser was used to dose about 100 t O_2.

The direct effects of oxygenation on the surface water quality cannot be readily quantified due to the significant reduction of the external phosphorus loading during the oxygenation period. In 1984 (before oxygenation), the phosphorus loading was estimated to approximately 1.3 g P m^{-2} y^{-1} and in 2000 to 0.7 g P m^{-2} y^{-1}, i.e. almost a 50% reduction. The reduced phosphorus loading can be ascribed to the closure of several fish farms during the period 1985–1988 and to the diversion of sewage from scattered dwellings in the catchment. Based on mass balance measurements it has been calculated that from 1984 to 1994 phosphorus was released from the lake at rates between 0.1 and 0.7 g P m^{-2} y^{-1}, while phosphorus since 2000 has been retained with rates between 0.03 and 0.4 g P m^{-2} y^{-1} (Liboriussen et al., 2007). Throughout the period nitrogen loading to Lake Hald has been relatively constant, approximately 44 g N m^{-2} y^{-1}.

Lake Vedsted

The oxygenation of Lake Vedsted was initiated in 1995. In 2002–2003, the lake was not oxygenated and the treatment was finally stopped in 2007 (Table 2). The average oxygen supply was 7.2 t O_2 y^{-1}, corresponding to a supply rate of approximately 0.05 t O_2 d^{-1}. The lake has no direct inlet or outlet, and it is assumed that the external loading of the lake has only changed negligibly from the 1990 estimations of 13.8 g N m^{-2} y^{-1} and 0.3 g P m^{-2} y^{-1}.

Lake Viborg Nørresø

Lake Viborg Nørresø was oxygenated during 1996–2007 (Table 2). The lake is via a short stream connected with the slightly larger Lake Viborg Søndersø where fish removal (biomanipulation) has been undertaken for several years in order to restore this part of the lake. Both lakes have been heavily impacted by nutrient loading for many years, but in the late 1980s and the beginning of the 1990s various initiatives were undertaken in the lakes' catchments to reduce the loading. Overall, however, the external loading remains relatively high (1.3–1.8 g P m^{-2} y^{-1} and 35–50 g N m^{-2} y^{-1}) and has not decreased during the oxygenation period (Johansson et al., 2006). More oxygen was added in 2001–2005 (80–136 t O_2 y^{-1}) than in 1996–2000 (11–98 t O_2 y^{-1}), corresponding to a supply rate between 0.08 and 0.85 t O_2 d^{-1}.

Lake Torup

In Lake Torup the diffuser technique was only applied in 2002–2003 as the oxygenation was insufficient and the thermal stratification periodically broken in both years. Consequently, in 2004 a new method was tested, and subsequently applied, by which oxygen-poor bottom water was pumped to a land-based system in which the water was 250–300% saturated with oxygen in a cone before being pumped back to the deepest parts of the lake. In 2005–2007, oxygenation continued using this new method (Table 2). An advantage of the land-based method is that it may be used in lakes with a shallow hypolimnion or if the difference in density between the water in the epilimnion and hypolimnion is small and the risk of breaking the thermocline consequently high. Annual oxygen application ranged between 5.4 and 9.6 t, corresponding to a supply rate of 0.07–0.09 t O_2 d^{-1}. The external nutrient loading to Lake Torup was significantly reduced in the decades before oxygenation, but remained relatively constant during the actual oxygenation. The runoff is relatively modest, implying that the lake's potential for loss of nutrients via water runoff is limited.

Lake Fure

In Lake Fure oxygenation was conducted from 2003 to 2007 (Table 2). The annual oxygen supply has since then been 320–650 t O_2 y^{-1}, corresponding to 2.1–4.4 t O_2 d^{-1}. The external phosphorus and nitrogen loadings were estimated to 0.2–0.4 g m^{-2} y^{-1} and 4.3–9.6 g m^{-2} y^{-1}, respectively, and have not changed since the mid-1990s. Intensive fish removal (approximately 200 t) of mainly roach (*Rutilus rutilus*) and bream (*Abramis brama*) was carried out in the lake between 2003 and 2006.

Sampling and analyses

The oxygenation projects were mainly planned and run by the local counties that also collected most of the data used in this article. Oxygen, temperature and chemical depth profiles were usually determined once or twice monthly during lake stratification, while winter samplings were less frequent. Phosphorus was analysed by the ammonium molybdate spectrometric method (Koroleff, 1977), while total nitrogen (TN) was determined following digestion with peroxodisulphate (Solórzano & Sharp, 1980). Ammonium was determined by using the phenol hypochlorite method (Solórzano, 1969) and nitrate + nitrite via the cadmium reduction method. Chlorophyll *a* in the surface water (0–2 m) was determined spectrophotometrically following extraction with ethanol (Jespersen & Christoffersen, 1987). In Lake Hald means of the data from depths >25 m were used in the analyses, while the depths >10, >9, >7 and >25 m were used in Lake Viborg Nørresø, Lake Vedsted, Lake Torup and Lake Fure, respectively. Mean summer concentrations only included data from the stratified period, and thus varied among the lakes. The hypolimnetic volume was estimated from the average depths below the thermocline and lake morphology. Pre-treatment years for Lake Hald are 1980–1984, the first oxygenation period being 1985–1994 and the second oxygenation period 1995–1997 and 1999–2004. For Lake Viborg Nørresø pre-oxygenation is 1990–1995 and oxygenation is 1996–1999 and 2001–2006. For Lake Vedsted pre-oxygenation is 1988–1990 and 1994, while oxygenation is 1995–2001 and 2005. For Lake Fure pre-oxygenation years are 1998–2002 and the oxygenation is 2004–2006; however, for the chemical variables only data from 1990 and 1994 were available. For Lake Torup pre-oxygenation years are 1998–2001 and oxygenation years are 2002–2005.

Results

Effects on the bottom water

Oxygen

In Lake Fure the oxygen concentrations in the hypolimnion during stratification increased following oxygenation (Fig. 1). Prior to oxygenation concentrations <2 mg O_2 l^{-1} were frequently detected in the hypolimnion during prolonged periods in summer, but when treated the concentration was typically >6 mg O_2 l^{-1}. The mean summer (July–September) oxygen concentration increased from 1.4 before to 8.9 mg l^{-1} following oxygenation (Table 3).

In the other four lakes oxygenation had only a minor effect on the bottom water oxygen concentration (Fig. 1). In Lake Vedsted oxygen levels near the sediment were around 2 mg O_2 l^{-1} during most of the summer, and due to two unusual years (1988 and 1989) with relatively good oxygen conditions in the pre-treatment period, a slight decrease in the mean summer concentration was seen from 3.0 mg l^{-1} before to 2.2 mg l^{-1} when oxygenated (Table 3). Lake Torup and Lake Viborg Nørresø were generally more depleted and oxygen concentrations <1 mg O_2 l^{-1} were frequently registered in both lakes. In Lake Torup oxygenation led to improved oxygen conditions, particularly in August and September, and an overall increase occurred in the mean summer oxygen concentration from 0.3 mg l^{-1} before to 1.7 mg l^{-1} when the second oxygenation method was applied. In Lake Viborg Nørresø mean summer oxygen increased from 0.3 to 1.2 mg l^{-1} with oxygenation. In Lake Hald higher oxygen concentrations were observed in June–July; and a general increase in mean summer oxygen levels occurred, from 0.5 mg l^{-1} before oxygenation to 1.5 mg l^{-1} in 1985–1994 and 1.7 mg l^{-1} in 1995–2004 (Table 3).

Temperature

The bottom water temperature of the five lakes was affected differently (Fig. 1). In the two deepest lakes, Lake Hald and Lake Fure, temperatures tended to increase 1–2°C in late summer during oxygenation; otherwise, only minor changes were observed. In the three remaining lakes temperatures were higher during oxygenation for most of the summer. The most marked temperature increase was seen in Lake Torup where the bottom water mean temperature increased 4–6°C during the summer period. This substantial change reflects that the thermocline was occasionally broken by the first oxygenation method and that the second method, involving oxygenation of bottom water onshore, entailed higher temperature and decreased stability of the thermocline, though it persisted in summer during 2004–2006.

Phosphorus

Oxygenation resulted in considerably lower accumulation of phosphorus in the bottom water of all five lakes. In Lake Hald, Lake Viborg Nørresø and Lake

Fure ortho-phosphate typically accounts for more than 80% of the total phosphorus (TP) pool in the hypolimnion (Fig. 2). The most marked effect was observed in Lake Hald where TP decreased from 800 μg P l^{-1} before oxygenation to approximately 200 μg P l^{-1} when oxygenated. The reduction was larger during the second (1995–2004) than during the first period (1985–1994) despite a general halving of the oxygen input from the first to the second period. In Lake Viborg Nørresø phosphorus accumulated during the summer, but the accumulation was lower during the oxygenation period where phosphorus concentrations of 400 μg P l^{-1} compared to 600 μg P l^{-1} before oxygenation were observed. In the other three lakes the pre-oxygenation phosphorus concentration was generally <400 μg P l^{-1} compared to 150 μg P l^{-1} during oxygenation.

In Lake Hald and Lake Vedsted oxygenation was stopped for 1 and 2 years, respectively, after which it was restarted and continued during the following years (Table 2). In both lakes a marked increase in the hypolimnetic phosphorus content was observed in years without oxygenation compared to the years with oxygenation (Fig. 3). In Lake Hald the concentration in summer almost doubled from approximately 80 μg P l^{-1} to more than 160 μg P l^{-1}, while in Lake Vedsted the increase was from approximately 150 μg P l^{-1} to 600 μg P l^{-1}, and the maximum concentrations even reached higher levels than before oxygenation; thus concentrations as high as 800 μg P l^{-1} were observed compared to a maximum of 400 μg P l^{-1} before the oxygenation.

Nitrogen

The concentration of TN in the bottom water decreased during oxygenation, but in Lake Hald and Lake Viborg Nørresø the reduction was not as marked as for phosphorus (Fig. 4). Data on hypolimnetic ammonia and nitrate concentrations were not available for Lake Fure, but measurements from the four other lakes indicate that the declining TN level was mainly the result of lower accumulation of ammonia in the bottom water in summer (Fig. 4). In Lake Hald nitrate concentrations increased during oxygenation, while in the other lakes only moderate changes in nitrate were observed.

Fig. 1 Seasonal development in bottom water oxygen concentration and temperature prior to and during oxygenation in Lake Hald (depths > 25 m), Lake Viborg Nørresø (depths > 10 m), Lake Vedsted (depths > 9 m), Lake Torup (depths > 7 m) and Lake Fure (depths > 25 m). Pre-oxygenation (*black boxes*), first oxygenation period (*grey boxes*) and second oxygenation period (*open boxes*) (only Lake Hald). Pre-oxygenation years for Lake Hald are 1980–1984, the first oxygenation period being 1985–1994 and the second oxygenation period 1995–1997 and 1999–2004. For Lake Viborg Nørresø pre-oxygenation is 1990–1995 and oxygenation is 1996–1999 and 2001–2006. For Lake Vedsted pre-oxygenation is 1988–1990 and 1994 while oxygenation is 1995–2001 and 2005. For Lake Fure pre-oxygenation years include 1998–2002 and the oxygenation years are 2004–2006. Data on chemical variables in Lake Fure are available only for 1990 and 1994. For Lake Torup pre-oxygenation years are 1998–2001 and oxygenation years are 2002–2005. *Grey* indicates when the lake is typically stratified ▶

Effects on surface water

Chlorophyll a and water transparency

Whereas oxygenation had clear effects on nutrient concentrations in the hypolimnion, its impact on surface water quality was less clear. The trophic state of Lake Hald has markedly improved concurrently with the oxygenation. The mean summer chlorophyll concentration decreased from 62 μg l^{-1} in 1979–1984 to 13 μg l^{-1} in 2004–2006, while Secchi depth increased from 2–3 m to approximately 5 m (Fig. 5). Mean summer TP decreased from 150 μg l^{-1} in 1984 to 19 μg l^{-1} in 2006, and algal blooms became less frequent. However, it is unclear to which extent the changes in surface water quality can be ascribed to oxygenation as the external nutrient loading, particularly from fish ponds, was substantially reduced during the oxygenation period.

In Lake Vedsted, Secchi depth increased and the chlorophyll concentration decreased in the first few years following oxygenation. Since then, Secchi depth and chlorophyll have varied greatly. Yet, even though no uniform effect of oxygenation is found, there is still a general improvement compared to the pre-oxygenation period (Fig. 5). The TP concentration in the surface water also varied considerably during the oxygenation period and in 1999–2000 it was higher than prior to oxygenation.

Effects of oxygenation on the surface water quality of Lake Viborg Nørresø have been limited. The

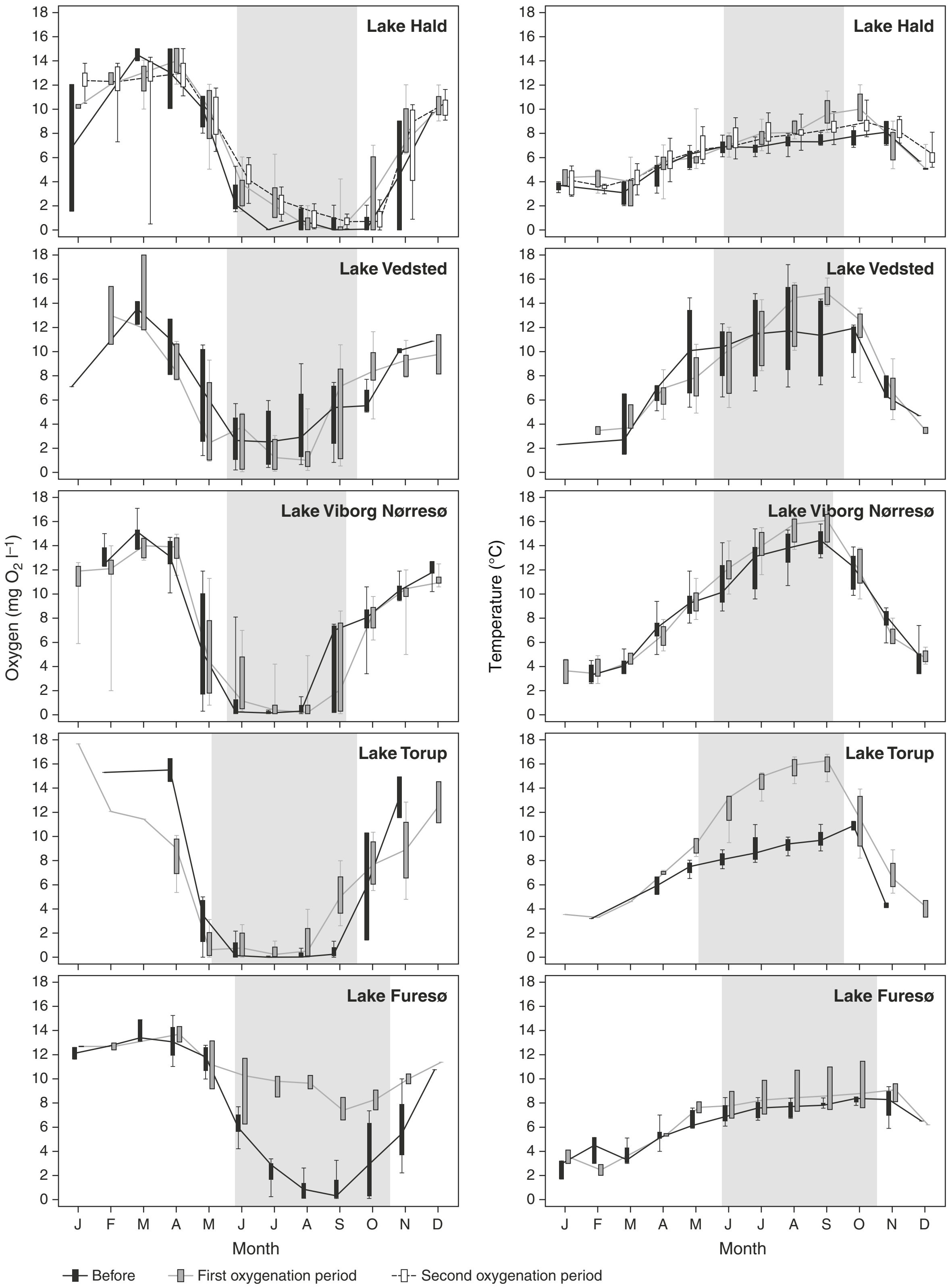

Lake Hald
Lake Vedsted
Lake Viborg Nørresø
Lake Torup
Lake Furesø
Oxygen (mg O2 l−1)
Temperature (°C)
J F M A M J J A S O N D
Month
Before
First oxygenation period
Second oxygenation period

Table 3 Summary of the hypolimnetic water quality responses in five Danish lakes exposed to hypolimnetic oxygenation

	Period	Mean summer dissolved oxygen (mg l^{-1})		Mean summer reduction from pre-oxygenation to oxygenation (%)	
		Pre-oxygenation	Oxygenation	Total phosphorus	Ammonia
Lake Hald	July–August	0.5	1.5 (1.7)	88	88
Lake Vedsted	June–August	3.0	2.2	49	48
Lake Viborg Nørresø	July–August	0.3	1.2	45	33
Lake Torup[a]	June–August	0.3	1.7	38	42
Lake Fure[b]	July–September	1.4	8.9	54	–

Mean summer concentrations were defined for each lake to only include data collected during stratification. *Lake Hald* pre-oxygenation (1980–1984), the first oxygenation period (1985–1994) and in parenthesis the second oxygenation period (1995–1997 and 1999–2004). *Lake Viborg Nørresø* pre-oxygenation (1990–1995) and oxygenation (1996–1999 and 2001–2006). *Lake Vedsted* pre-oxygenation (1988–1990 and 1994) and oxygenation (1995–2001 and 2005). *Lake Fure* pre-oxygenation (1998–2002) and oxygenation (2004–2006). *Lake Torup* pre-oxygenation (1998–2001) and oxygenation (2002–2005)

[a] Different oxygenation methods in 2002–2003 and in 2004–2007

[b] Removal of 200 t cyprinids 2003–2006

chlorophyll level of 40–50 μg l^{-1} has remained relatively constant, whereas Secchi depth has increased from approximately 1.7 m to approximately 2 m in recent years.

The oxygenation of Lake Torup has only functioned optimally without thermocline breakdown for a few years, and with the large interannual fluctuations the general development of the surface water cannot be readily described. However, a tendency towards improved Secchi depth has been observed in recent years and a maximum of 1.7 m was reached in 2006 (Fig. 5). The total algal biomass has also been reduced by almost 35% and blooms of the cyanobacteria *Planktothrix prolifera* frequently observed in the pre-oxygenation period have not occurred in recent years. Moreover, the coverage of submerged vegetation has increased from 3% in 2004 to 14% in 2007, while the maximum depth for plant growth has increased from 2 to 3.8 m during the same period (Liboriussen et al., 2007).

So far, no clear effect of oxygenation on the surface water quality has been detected in Lake Fure, even though the treatment was combined with a major reduction of the planktivorous fish stock. During recent decades, there has, though, been a general increase in mean and maximum summer Secchi depth in Lake Fure (Fig. 5), but this coincides with a reduction of the external phosphorus loading by approximately 50% since 1980.

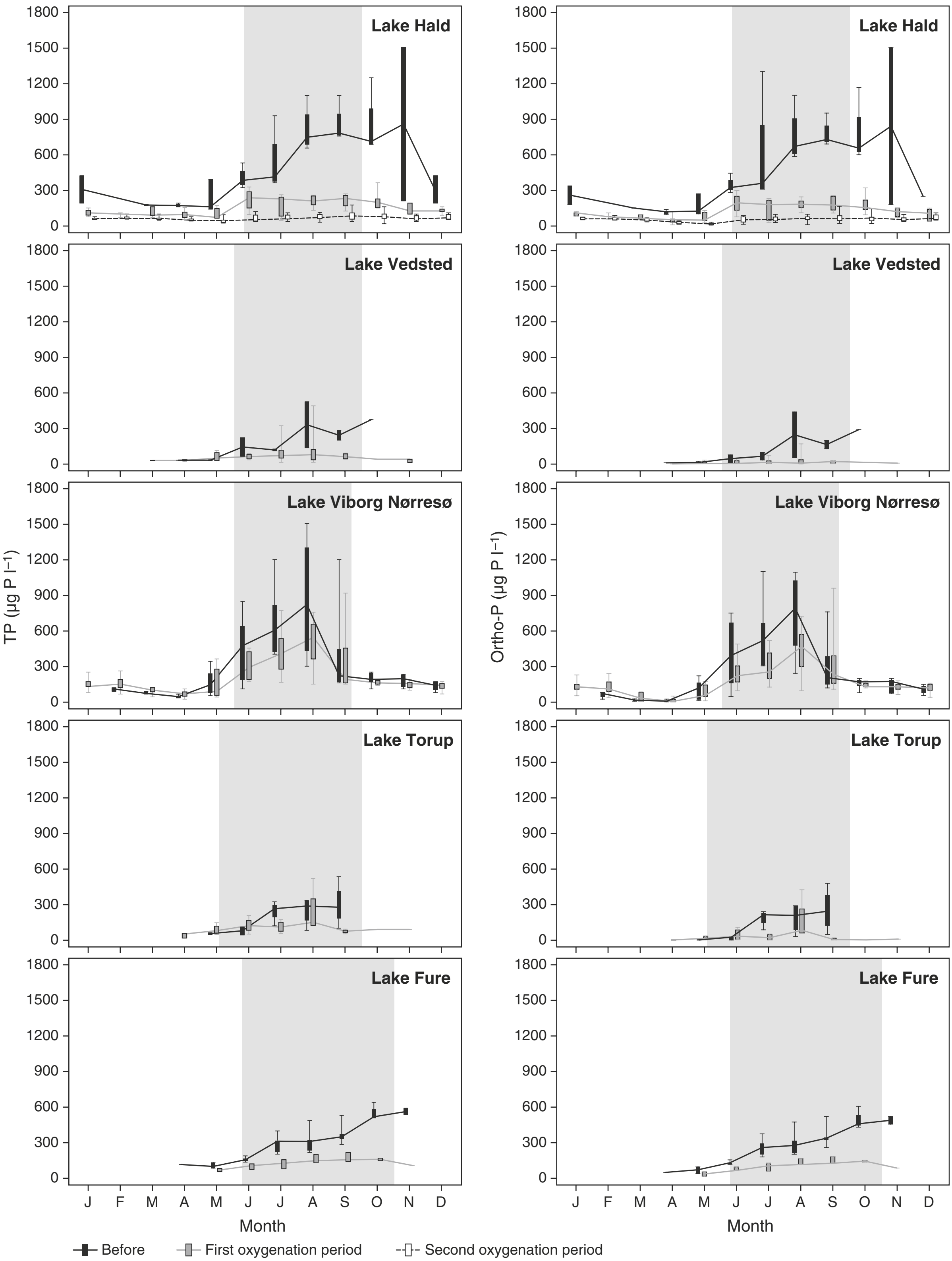
Discussion

Oxygen

In four of the five oxygenated Danish lakes hypolimnetic oxygenation led to only minor improvements of the concentration of dissolved oxygen in the hypolimnion, resulting in mean summer concentrations of 1.2–2.2 mg O_2 l^{-1}. This differs from the overall conclusions of a case story review of nine lakes by Beutel & Horne (1999) who found that oxygenation generally resulted in larger improvements in the hypolimnetic oxygen level with mean summer dissolved oxygen above 4 mg O_2 l^{-1}. In our study, the largest improvements in oxygen level usually occurred during the first months of stratification, whereas no or minor improvements were seen later in the season. This probably reflects that oxygen consumption at the sediment surface increases during summer due to increased amounts of easy degradable organic matter and increasing temperature.

Inability of oxygenation to maintain an oxic hypolimnion throughout the stratified period has also been found in other lakes. In the Swiss lakes, Lake

Fig. 2 Seasonal development in the bottom water concentrations of total phosphorus (TP) and orthophosphate (ortho-P) before and during oxygenation in Lake Hald, Lake Viborg Nørresø, Lake Vedsted, Lake Torup and Lake Fure. *Grey* indicates when the lake is typically stratified. For more details see the legend of Fig. 1 ▶


Lake Hald
Lake Vedsted
Lake Viborg Nørresø
Lake Torup
Lake Fure
TP (µg P l−1)
Ortho-P (µg P l−1)
1800
1500
1200
900
600
300
0
J F M A M J J A S O N D
Month
Before
First oxygenation period
Second oxygenation period

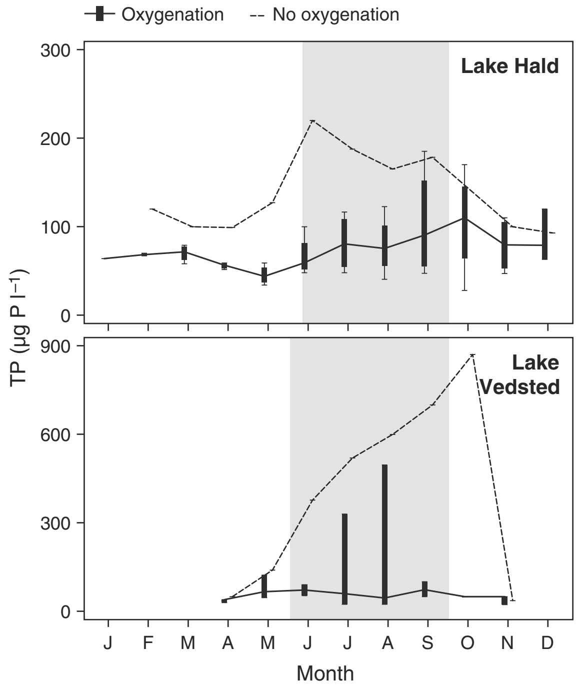


Fig. 3 The effect on the bottom water concentration of total phosphorus (TP) at the cessation of oxygenation in Lake Hald (depths > 25 m) and Lake Vedsted (depths > 9 m). Oxygenation years for Lake Hald are 1996–1997 and 1999–2000 and the year without oxygenation is 1998. For Lake Vedsted the years with oxygenation comprise 2000–2001 and 2005, while 2002 represents the year without oxygenation. *Grey* indicates when the lake is typically stratified

Fig. 4 Seasonal development in the bottom water's concentrations of total nitrogen (TN), ammonia (NH_4) and nitrate + nitrite ($NO_3 + NO_2$) prior to and during hypolimnetic oxygenation in Lake Hald, Lake Viborg Nørresø, Lake Vedsted and Lake Torup and of TN in Lake Fure. *Grey* indicates when the lake is typically stratified. For more details see the legend of Fig. 1

Baldegg and Lake Hallwil, low oxygen levels near the bottom were experienced in the second half of the year even after >15 years of oxygenation in summer and artificial mixing in winter (Müller & Stadelmann, 2004). Likewise, in Irondequoit Bay (New York, USA) dissolved oxygen in the hypolimnion dropped below 0.5 mg l^{-1} in summer despite a continuous oxygen supply of approximately 1.7 t d^{-1} (Klumb et al., 2004), and in Heart Lake (Canada) summer concentrations around 2 mg l^{-1} were seen despite a continuous hypolimnetic oxygen supply (Gemza, 1997). Although comparable oxygen supplies were applied to the studied Danish lakes, only the deepest and largest of the lakes, Lake Fure, experienced significant improvements (mean summer increase from 1.4 to 8.9 mg O_2 l^{-1}) of the oxygen concentration in the bottom waters throughout the entire stratified period. This lake differs from the other lakes, and most importantly from the morphologically similar Lake Hald, by receiving the lowest external nutrient input and by having a 5–10 times higher hydraulic retention time. As described by Jeppesen et al. (1991), this probably induces lower rates of sedimentation and a smaller pool of settled organic material at the sediment of Lake Fure relative to the other lakes as a larger fraction of the settling material is decomposed in the water column before reaching the hypolimnion. The importance of water depth in segregating oxygen demand between the water column and the sediment was also discussed by Beutel (2003). He found that shallow lakes tend to have a larger fraction of their total oxygen demand exerted in the sediment compared to deeper lakes of similar trophic status. Due to this, shallow lakes are more susceptible to induced oxygen demand caused by the increased mixing at the water–sediment interface occurring during hypolimnetic oxygenation. Beutel (2003) found that bottom water velocities ranging from 3 to 4 cm s^{-1} increased the sediment oxygen demand by a factor of approximately two. Although induced oxygen demand was not quantified in our study lakes, it is likely that this may at least partly be responsible for the limited effect of the oxygenation on the hypolimnetic oxygen level.

Another important issue may be the effectiveness of the oxygenation systems. As discussed by Wüest et al. (1992), the initial bubble size and water depth are key factors that determine the efficiency of the ability for a rising oxygen bubble to dissolve into the surrounding water column. Lower water depth and lower effectiveness of the oxygenation systems may thus be key issues for the limited effect on the hypolimnetic oxygen level compared to the effects reported in the case story review by Beutel and Horne (1999). These lakes were generally deeper and most of them also larger than the Danish lakes and therefore then probably comparable to the results obtained in Lake Fure, in which the efficiency of the oxygenation was 93–95%.

Although only minor improvements of the bottom water oxygen level were found, hypolimnetic oxygenation may still have had considerable beneficial

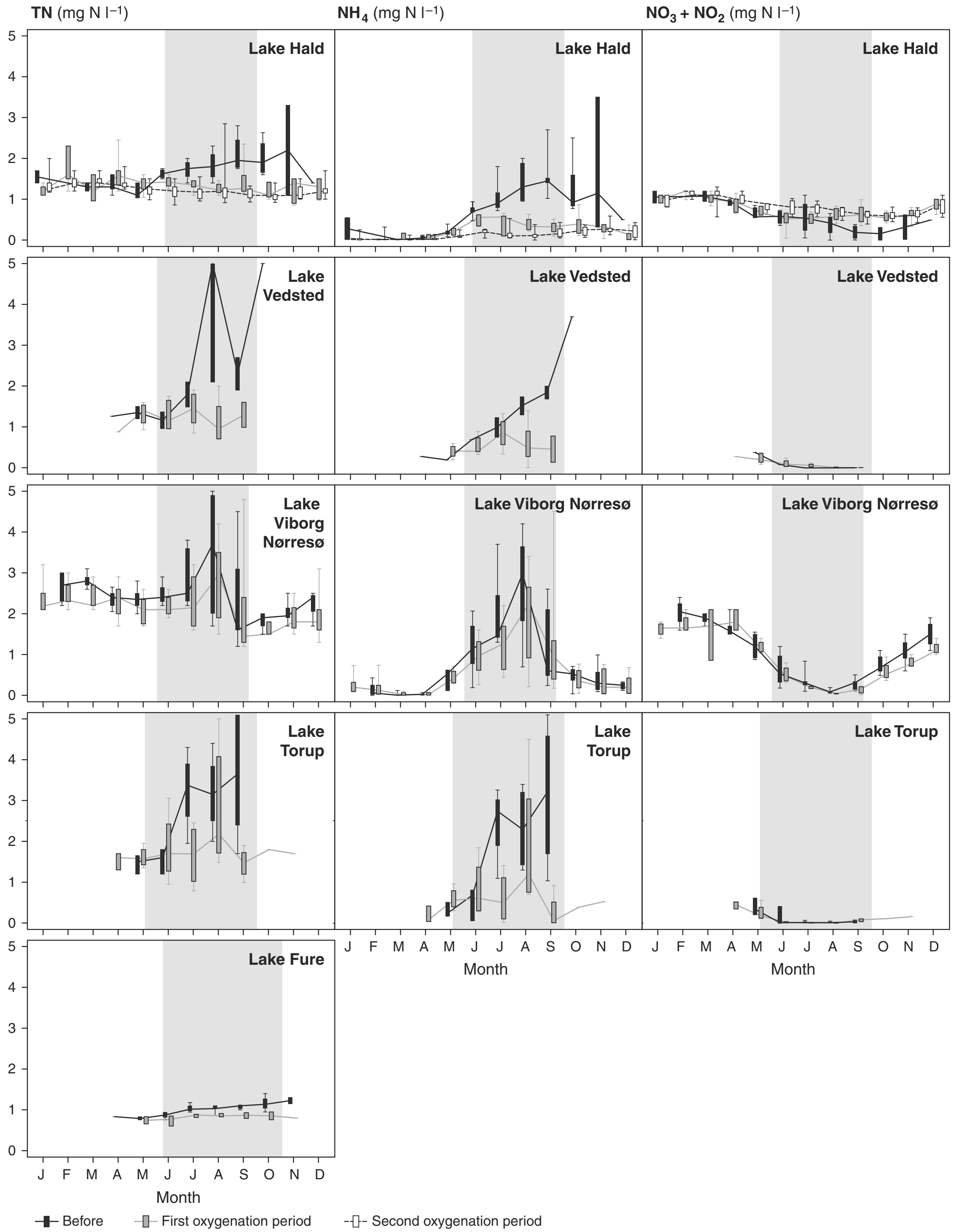
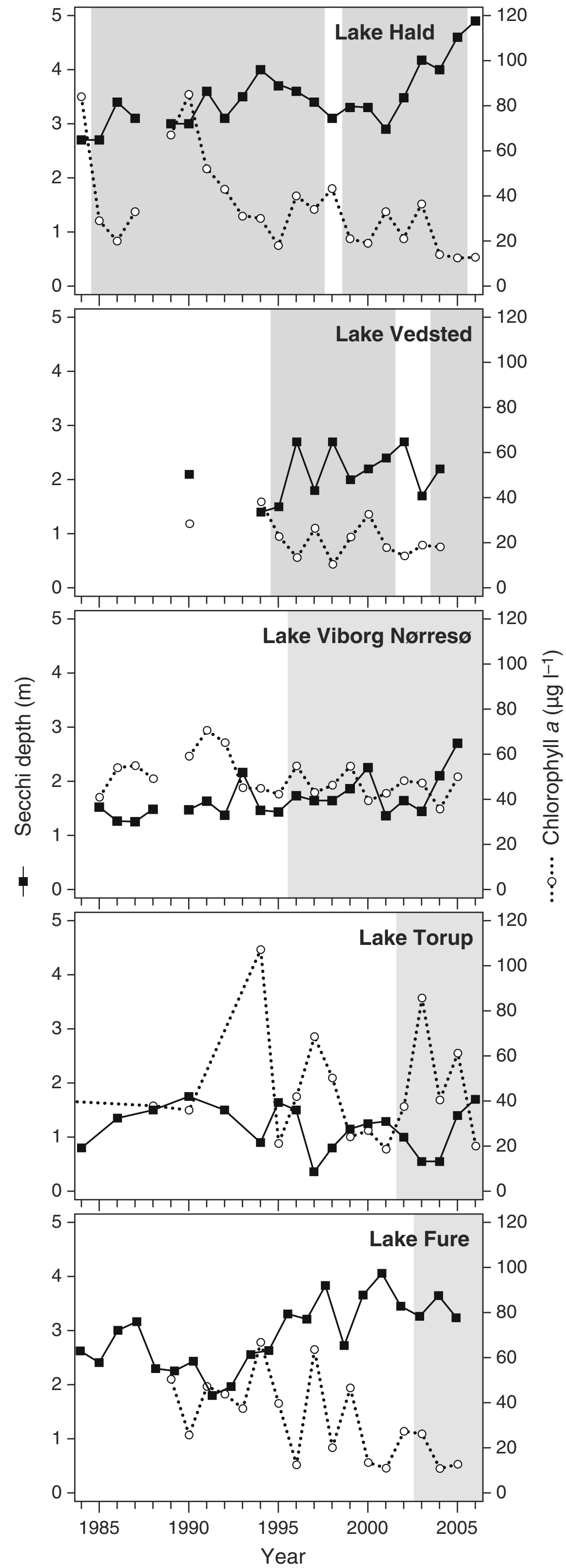

TN (mg N l−1)
NH4 (mg N l−1)
NO3 + NO2 (mg N l−1)
Lake Hald
Lake Vedsted
Lake Viborg Nørresø
Lake Torup
Lake Fure
J F M A M J J A S O N D
Month
Before
First oxygenation period
Second oxygenation period

Fig. 5 Mean summer Secchi depth and chlorophyll concentrations in Lake Hald, Lake Viborg Nørresø, Lake Vedsted, Lake Torup and Lake Fure. *Grey* indicates hypolimnetic oxygenation



effects on the aquatic biota as found by for example Dinsmore & Prepas (1997) and Müller & Stadelmann (2004). Yet, the beneficial effects on the biota were not systematically quantified in the studied lakes, but in both Lake Fure and in Lake Hald chironomids recolonised the deepest parts of the lake (Liboriussen et al., 2007). Furthermore, in Lake Fure oxygenation also led to an expansion of the habitat for fish, which are now found at greater depths, while the relict crustaceans *Mysis relicta*, which is distinct from all other European species, and *Pallasea quadrispinosa* now thrive better and are found in the hypolimnion in the summer (www.furesoeprojekt.dk final report).

Temperature

An increase of 1 to 2°C in the hypolimnetic water temperature as a consequence of the oxygen treatment, as seen in four of the five lakes, was also found in the north basin of Amisk Lake by Dinsmore & Prepas (1997). They concluded that the impact of such an increase on the density of profundal macroinvertebrates was minor relative to the effects of the improved oxygen concentrations. However, increased bottom temperatures, as particularly observed in Lake Torup, will decrease the stability of the thermocline and increase the possibility of a complete overturn of the water column earlier than normally seen, which will ultimately increase the risk of massive algal blooms (Becker et al., 2006). In Lake Serraia oxygenation by high-pressure oxygen-rich water injection by hypolimnetic jets induced a maximum increase of about 9°C in the hypolimnion (Ragazzi et al., 2007). Due to this increase thermal stratification did not fully develop and the lake was subject to an anticipated autumnal mixing with an unusual algal bloom in August. Increased bottom temperatures may furthermore stimulate mineralisation and oxidising (Thamdrup et al., 1998) and thus increase the consumption of oxidising compounds and accelerate the accumulation of nutrients in the hypolimnion. Combined with an improved oxygen concentration at the sediment–water interface, higher temperatures may also drive resting eggs and cysts to hatch earlier than usual (Bürgi & Stadelmann, 1991), changing the seasonality of the planktonic communities.

Nutrients

Phosphorus concentration in the hypolimnion during stratification was markedly reduced in all the lakes. Similar results have previously been reported by others (Ashley, 1983; Matinvesi, 1996; Prepas & Burke, 1997; Beutel & Horne, 1999). By contrast, based on 10-year artificial mixing and hypolimnetic oxygenation of Lake Baldegg and Lake Sempach, Gächter & Wehrli (1998) were not able to detect any decrease in internal phosphorus loading or an increase in permanent phosphorus retention. They showed that irrespective of the oxic conditions in the hypolimnion the sediment–water interface remained anoxic due to unchanged high sedimentation rates of organic matter. Moosmann et al. (2006) furthermore concluded that the phosphorus concentration in the surface lake water, rather than the hypolimnetic concentrations of dissolved oxygen, determines phosphorus retention in oxygenated, eutrophic lakes with anoxic sediments. Though phosphorus accumulation calculations in our study did not include the entire pool of phosphorus in the hypolimnion, but simply were based on changes in the bottom water concentration, the results clearly suggest that phosphorus accumulation is reduced by oxygenation, as oxygenation only induced minor changes in the total hypolimnion volume (−6 to 14%). However, in Lake Vedsted the depth of the thermocline was reduced by almost 30% from the pre-oxygenation to the oxygenation period (authors' unpublished data), and in this lake the increased hypolimnion volume may have been important for the total nutrient concentrations.

Our results indicate that long-term oxygenation is needed to maintain the positive effect on the phosphorus accumulation. The marked increase in hypolimnetic phosphorus accumulation when oxygenation was stopped in Lake Hald after 13 years and in Lake Vedsted after 7 years clearly illustrates the risk of new incidents of phosphorus accumulation in the hypolimnion if the oxygen treatment is permanently stopped. However, the results from Lake Hald where oxygenation was conducted for the longest time period indicate that some permanent effects might be achieved as the phosphorus accumulation was not as marked as before the oxygenation.

Ultimately, the relatively limited improvements of the hypolimnetic oxygen level is a result of the high oxygen consumption at the sediment surface (decomposition of organic matter and conversion of ammonium to nitrate) as described by other studies (Matinvesi, 1996; Matthews & Effler, 2006). Eventually the pool of easy degradable organic matter will decrease, resulting in a steady decrease in the annual oxygen demand. This is probably what happened in Lake Hald after 10–15 years of oxygenation. Here, the phosphorus accumulation in the hypolimnion was higher in the first years with oxygenation than during the most recent years despite a reduced oxygen supply during the latter period. In Lake Hald a reduced external loading leading to reduced nutrient concentration and a lower production in the surface water, and hence lower sedimentation of new organic matter to the lake bottom may, however, also be important for the decreasing oxygen demand in this lake.

A potential negative side-effect of the oxygenation is that an oxygenation-induced stimulation of the mineralisation rate—maybe also via increased denitrification activity caused by the oxidation of ammonia—may enhance the pool of inorganic phosphorus in the sediment. If this phosphorus, which otherwise might have been buried permanently as organically bound phosphorus is not bound to inorganic substances such as oxidised iron hydroxides, there is a risk that oxygenation will create an increased mobile phosphorus pool that might be released when oxygenation is stopped.

Reduced accumulation of hypolimnetic ammonia as a result of oxygenation was obvious in the four lakes where inorganic nitrogen was regularly measured. At a well-oxygenated sediment–water interface the ammonia released from sediment is immediately oxidised, hence diminishing or inhibiting ammonia accumulation (Prepas & Burke, 1997; Gächter & Wehrli, 1998; Beutel et al., 2007). By incubating lake sediment in experimental chambers Rysgaard et al. (1994) found that ammonia accumulation in the overlaying water column decreased from fluxes around 80 mg N m^{-2} d^{-1} at anoxic conditions to roughly 10 mg N m^{-2} d^{-1} at well-oxygenated conditions, and in Camanche Reservoir oxygenation resulted in a decrease in the peak level of hypolimnetic ammonia from around 1.4 to below 0.2 mg N l^{-1}(Beutel, 2006). Anoxic release rates of ammonia have been found to show a strong correlation with the trophic state of the lake. Beutel (2006) reported rates below 5 mg N m^{-2} d^{-1} at oligo-mesotrophic sites, while eutrophic sites typically had rates >15 mg N m^{-2} d^{-1}. This correlation to trophic state may explain why the ammonia concentration now retains the lowest levels in Lake Hald, which is the least eutrophic system. In Lake Hald nitrification of ammonia to nitrate was implied by an increased level of nitrate concurrently with the reduction of ammonia. The increase did, however, not fully balance the ammonia reduction, thus resulting in a general net decrease in the mass of inorganic nitrogen. As seen for the three other lakes, promotion of nitrification by oxygenation cannot always be registered as an increased nitrate concentration likely as a result of denitrification. Likewise, in the oxygenated north basin in Amisk Lake no change in the nitrate level was observed (Prepas & Burke, 1997), and in Lake Sempach decreased concentrations of both ammonia and nitrate were seen during the first years of oxygenation, and after more than 4 years significantly less inorganic nitrogen accumulated in the hypolimnion during summer stratification (Höhener & Gächter, 1994).

Accumulation of ammonia typically started in May–June, as soon as the thermocline and close to anoxic conditions were developed. In some of the lakes a late-season acceleration in the ammonia accumulation occurred, which has been suggested as a result from the decay of late summer cyanobacterial blooms producing organic nitrogen via biological fixation (Beutel, 2001). No general distinct seasonal pattern could be traced for when oxygenation resulted in the highest reduction in ammonia in our lakes. In Lake Viborg Nørresø a reduction was only registered in June–August, while the largest reduction occurred between August and November in the three other lakes. In Lake Hald both phosphorus and ammonia were reduced by 88% by the oxygenation, while the mean reductions were approximately 50% in Lake Vedsted and 40% in Lake Torup (Table 3). In accordance with this, results from Upper San Leandro Reservoir (Horne et al., 2003) and nine other lakes/reservoirs summarised by Beutel & Horne (1999) report reductions of 60–95% in the hypolimnetic ammonia when the lake is oxygenated, while hypolimnetic oxygenation reduced mean total inorganic nitrogen by 75% in Lake Heart and 25% in Whittaker Lake (Gemza, 1997).

The marked effects of oxygenation on bottom water accumulation of phosphorus probably reflect the classical redox sensitive binding of phosphorus to oxidised iron compounds in the sediment (Einsele, 1936; Mortimer, 1941). The question is whether the oxygenation actually leads to improved lake water conditions as those, reported by, for example Webb et al. (1997), who found decreased summer phytoplankton biomass and less dominance of cyanobacteria in the first year with oxygenation of Amisk Lake, and by Gemza (1997) who found improvements of the annual median water clarity from 1.9 m to over 3.0 m in Heart Lake. In our study, clear effects on surface water quality were only seen in Lake Hald, and here it is difficult to disentangle the effects of oxygenation from the effects of the reduced external phosphorus loading. In the other lakes, there were no immediate indications that the reduced phosphorus content was reflected in improved lake water quality. The lacking effect on surface water quality in the four other lakes may reflect that the external phosphorus loading is still too high or that the impact of the decreased hypolimnetic accumulation does not translate adequately to the phosphorus content of the surface water. This is furthermore indicated by relatively high phosphorus concentrations in the epilimnion of the five lakes that within the last years have ranged between 19 and 98 µg TP l^{-1}. Several of the oxygenated Danish lakes are also relatively shallow, implying that large parts of the lake are not stratified and from these parts phosphorus is therefore continuously released to the surface water throughout the summer. In shallow, eutrophic Danish lakes water phosphorus concentrations are to a large extent controlled by the internal loading of phosphorus during summer (Søndergaard et al., 1999).

Summary

In conclusion, oxygenation led to only minor improvements of the oxygen level in most lakes, but had clear diminishing effects on the accumulation of phosphorus and ammonia in the hypolimnion of five Danish lakes during summer stratification. However, at cessation of oxygenation accumulation increased again and it is uncertain whether oxygenation can be used to create permanent improvements and recovery of productive oxygen depleted lakes. Restoration by oxygenation is hence a long-lasting project if effects are to be sustained over time, at least at the nutrient levels exhibited in this study. Hypolimnetic oxygenation of stratified eutrophic lakes should therefore only be seen as a temporary restoration strategy to reduce the internal nutrient accumulation and improve the living conditions for organisms during anoxic periods. As also pointed out by other studies (e.g. by Gächter (1987) and Gächter & Wehrli (1998)) the oxygen treatment should be accompanied by reduced nutrient inputs if permanent improvements of the lake water quality are to be obtained.

Acknowledgements We wish to thank the former Danish counties for access to the data used in the analyses. The study was supported by the EU EUROLIMPACS project (www.eurolimpacs.ucl.ac.uk) on the effects of climate changes on aquatic ecosystems and the Danish Centre for Lake Restoration (CLEAR—a VILLUM KANN RASMUSSEN Centre of Excellence project). We also thank Anne Mette Poulsen and Juana Jacobsen at the National Environmental Research Institute for editorial and layout assistance.

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