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RESEARCH ARTICLE

Internal phosphorus loading due to sediment anoxia in shallow areas: implications for lake aeration treatments

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Abstract

Shallow lake sediments may be anoxic despite overlying aerated water. In the current study, we aimed to ascertain the contribution of shallow areas to internal phosphorus (P) loading due to sediment anoxia in stratifying lakes. Moreover, we analyzed relationships of the key water quality variables with internal P loading due to sediment anoxia originating solely from stratifying areas (IP_{obs}) and that accounting also for the shallow areas (IP_{pred}) for a set of Finnish lakes, including intentionally aerated and non-aerated lakes. Finally, using a broader set of lakes worldwide, we established a specific combination of lake characteristics that predict sediment P release due to sediment anoxia and linked it to the practices of aeration. Our results showed that shallow lake areas (a difference between IP_{pred} and IP_{obs}) contributed about half of the total P flux due to sediment anoxia. While all of the studied water quality variables related significantly to IP_{pred}, only the concentration of total phosphorus (TP) in the near-bottom water layer related significantly to IP_{obs}. This indicates the key importance of P release of shallow areas for water quality. The concentrations of TP in the surface water layer and chlorophyll *a* were significantly dependent on IP_{pred} irrespectively of the treatment (aerated lakes or not). P supply from shallow areas may affect aeration effectiveness in stratifying lakes. IP_{pred} was found to be dependent on the specific combination of lake characteristics (including mean and maximum depth, lake and catchment area, external P loading) PC3, driven mainly by external P loading. Hence, external load reduction should be considered as the first priority in lake water quality management. By linking the dependence of IP_{pred} on PC3 to aeration practices, we determined the conditions that promise increased effectiveness of aeration treatments.

Keywords Internal phosphorus loading · Sediment anoxia · Shallow areas · Aeration

Introduction

Lakes act as traps accumulating nutrients at the bottom (Granéli 1999; Søndergaard et al. 2003). However, under certain conditions these nutrients can be recycled back to the overlying water column, resulting in adverse effects for the lake water quality. Particularly, the release of phosphorus (P) from sediments has hindered restoration of lake water quality worldwide by delaying the response to reduced nutrient loading from the catchment (i.e., external loading; Sas 1990; Jeppesen et al. 2005). Moreover, internal P loading is often regarded to have more influence on algal biomass than external loading, as it is in a more bioavailable form (Nürnberg et al. 2013a; Bormans et al. 2016). This renders lake sediments the key targets for in-lake measures to reduce phosphorus supply to phytoplankton (Bormans et al. 2016; Nürnberg and LaZerte 2016).

The transport of P from sediments to the overlying water column is preceded by mobilization processes. These processes have been attributed predominantly to the changes in redox conditions. At low oxygen concentrations (redox potential below 200 mV) the sediment iron Fe(III) is reduced to Fe(II) resulting in the breakdown of Fe–P complexes with the subsequent dissolution of the associated phosphate (Mortimer 1941, 1942). The phenomenon

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has been well documented for deep stratifying lakes that display obvious periods of hypolimnetic anoxia. In shallow (unstratified) lakes, the importance of this P mobilization mechanism might be high, but would be obscured by almost continuous vertical mixing; therefore, quantifying anoxia-generated internal P loading is generally difficult for these lakes (Nürnberg 2004, 2009). Well-oxidized sediment surface can be a sink of P via sorbing settling P and preventing P of deeper sediments from escaping. However, this mechanism may lessen over diel and seasonal cycles especially in enriched systems, turning shallow sediments to an important P source (Smith et al. 2011). Moreover, even this well-oxidized sediment surface does not preclude the potential release of mobile P to the overlying water column due to existing gradients with high porewater concentrations compared to low P concentrations in the overlying water and sediment disturbances (Tammeorg et al. 2015, 2016). The relevance of the problem is particularly high given that deep stratifying lakes may also have extensive shallow areas. Moreover, it was found recently that anoxia-generated P release in the hypolimnion is of minor importance in lake water quality management (Tammeorg et al. 2017).

Restoration of deep stratifying lakes has relied mostly on improving oxygen conditions of the hypolimnion (Cooke et al. 2005; Bormans et al. 2016; Visser et al. 2016). However, there is an increasing number of studies reporting only minor effects of these measures on lake water quality (Gächter and Wehrli 1998; Nürnberg et al. 2003; Liboriussen et al. 2009; Horppila et al. 2015, 2017; Kuha et al. 2016). Although lack of success can just be caused by technical deficiencies, it can also demonstrate poor understanding of the interactions between oxygen deficit, benthic P release, and water quality (Caraco et al. 1989; Golterman 2001; Prairie et al. 2002; Kopáček et al. 2005; Hupfer and Lewandowski 2008; Molot et al. 2014; Tammeorg et al. 2017).

In the current study, we demonstrate that sediment phosphorus release is of crucial importance for lake ecosystem management by investigating the theory and underlying assumptions for the practices of lake restoration by oxygen management. First, we ascertained the importance of internal P loading from shallow areas, where the lake bed sediments may be anoxic despite being overlain by mixed, aerated water in the epilimnion. Next, we compared the relationships of key water quality variables with internal P loading due to sediment anoxia originating solely from stratifying areas with that including the shallow areas (as defined above) for a set of Finnish lakes. At this step, we separated aeration-treated lakes from untreated stratifying lakes. Finally, we ascertained a specific combination of lake characteristics that enables us to predict internal P loading due to sediment anoxia for a broader set of lakes worldwide and linked it to the practices of aeration.

Materials and methods

Study area

We used data for 56 lakes worldwide, including those from small to large, shallow to deep and oligotrophic to highly eutrophic (presented in Supplementary Material of Tammeorg et al. 2017). Thirty-three of 42 studied stratifying lakes and 12 of 14 non-stratifying lakes had the complete set of basic lake characteristics including mean and maximum depth, catchment area and lake area size, external P loading (Table 1). Twenty-five studied lakes are located in southern Finland with a range of lake area from 0.25 to 155 km^2, lake mean depth from 1.1 to 21 m, and trophic state from mesotrophic to hypertrophic. Nineteen of the Finnish lakes undergo periodic anoxia, generally in winter and in summer. Seven of them have been subjected to aeration, including Enonselkä, Tuusulanjärvi, Hormajärvi, Bodominjärvi, Mallusjärvi, Pusulanjärvi and Enäjärvi. These lakes were mainly treated by hypolimnetic aeration with Mixox-units (Water-Eco Ltd, Kuopio, Finland) that pump oxygen-rich epilimnetic water down to the hypolimnion without breaking stratification. In Tuusulanjärvi, destratification was intentionally applied since 1998 (Horppila et al. 2017). The duration of treatment application varied between lakes, being longest in case of Tuusulanjärvi and Enonselkä (Water-Eco Ltd., 2019).

Internal phosphorus loading due to sediment anoxia

The P loading from shallow lake areas that were overlain by mixed aerated water was determined as the difference between predicted (IP_{pred}) and observed (IP_{obs}) internal P loading. IP_{obs} is associated only with the deep

Table 1 Summary of the basic characteristics for 45 lakes (33 stratifying and 12 non-stratifying) with complete data sets (original data in Tammeorg et al. 2017)

Variable[a]	Unit	Mean	SD	Minimum	Maximum
CA	km^2	6299	21,626	1	122,000
D	m	9.3	14.0	1.1	90.0
D_{max}	m	24.5	37.9	2.6	251.0
LA	km^2	746	3852	0.1	25,821
IF	mg P m^{-2} y^{-1}	1528	5638	23	38,155

[a]The variables include: catchment area (CA), mean depth (D), maximum depth (D_{max}), lake area (LA), external loading of P (IF)

stratifying areas, i.e. areas where anoxia is evident. IP_{pred} (in mg P m^{-2} per summer, thereafter mg P m^{-2} sum^{-1}), i.e., internal P loading from anoxic surfaces of the entire lake (including those in both stratifying and shallow lake areas) was determined according to Eq. (1) (Nürnberg 2009):

$$IP_{pred} = AF_{pred} \times RR_{pred}, \tag{1}$$

where RR_{pred} is the P release rate under anoxic conditions. Anoxic sediments in eutrophic lakes release P at significantly higher rates than in lakes with lower trophic states (Nürnberg 1988, 1997; Carter and Dzialowski 2012), and mean values reported for the lakes worldwide ($n = 6$, 14, 40, 29 for oligo- to hypertrophic lakes; Nürnberg 1997) were used as approximation, where RR_{pred}: for oligotrophic 0 mg P m^{-2} d^{-1}, mesotrophic 6.1 mg P m^{-2} d^{-1}, eutrophic 10.8 mg P m^{-2} d^{-1} and hypertrophic lakes 25.6 mg P m^{-2} d^{-1}. Studied lakes were classified as oligotrophic (average epilimnetic summer TP < 10 µg/l), mesotrophic (10 < TP < 30 µg/l), eutrophic (30 < TP < 100 µg/l) and hypereutrophic (> 100 µg/l) based on the criteria by Nürnberg (1996). Despite long periods and extent of anoxia, P release rates in low-productive lakes (e.g., oligotrophic lakes stained with organic acids and deep-for-area morphometries) are negligible due to a lack of reductant-soluble P in the sediment, or due to aluminium (Al) fluxes from watersheds (Al compounds enable efficient binding of P; Kopáček et al. 2005).

AF_{pred} represents the sediment area potentially involved in P release modeled as anoxic factor (Nürnberg 2004):

$$AF_{pred} = -36.2 + 50.1\log\left(TP_{sum}\right) + 0.762\, z/A_o^{0.5}, \tag{2}$$

where AF_{pred}, summer AF (d $summer^{-1}$); z, mean depth (m); A_o, lake surface area (km^2); TP_{sum}, epilimnetic summer concentration of TP (µg l^{-1}).

The internal P loads resulting from the difference between IP_{pred} and IP_{obs} can be assumed to be mediated by redox processes in the upper sediments and at the sediment–water interface of the un-stratified areas because IP_{pred} is based on AF_{pred} (Eq. 2). That difference could be slightly enhanced by potential overestimation of the release rates by the release rate model, that is based on deep-water sediments of stratified lakes. Originally, the AF_{pred} model was developed with data of stratifying lakes (Nürnberg 1995, 2004). However, comparisons of different internal load approaches in polymictic lakes supported the use of AF_{pred} with anoxic release rates for eutrophic shallow and mixed lakes (Nürnberg 2005), in which large sediment surfaces can still be anoxic and actively releasing phosphorus. In other words, AF_{pred} adequately quantifies the sediment area of polymictic lakes, where redox-related P release occurs and thus also in shallow areas (i.e. areas, in which sediments are overlain by mixed water) of stratified lakes. There is no simple experimental way of determining such an area for unstratified lakes and lake sections.

The more eutrophic a lake is, the more likely is the difference between IP_{pred} and IP_{obs} because of different P release rates. In oligotrophic lakes, release rate of P is close to zero and there is not much contribution from either stratifying or shallow areas (despite that AF can be high), which is not the case of eutrophic lakes that have considerably higher release rates (while AF can be comparable to that in oligotrophic lakes). These relationships are important because nutrient-rich lakes are indeed the main targets in water quality management.

The values for IP_{obs} were reported in Tammeorg et al. (2017). For the Finnish lakes, the hypolimnetic accumulation of P (Nowlin et al. 2005) was a measure of IP_{obs} (mg P m^{-2} sum^{-1}). In the rest of the lakes, an approach similar to that in Eq. (1) was used, with the difference that the factors multiplied (RR_{obs} and AF_{obs}) were measured values. RR_{obs} is the release rate from core incubations reported in the literature for the specific lakes. Generally, the literature values for the experimentally derived RR values were reported to be similar to the RR measured in situ from hypolimnetic P mass increases, and thus, applicable to whole lakes (Nürnberg 1984, 1987, 1988). AF_{obs} is the product of the percentage of anoxic areas and duration of anoxia revealed by monitored dissolved oxygen profiles (Nürnberg 2004). In stratified lakes, sediment anoxia estimated from anoxia monitored in the water is similar to modelled anoxia, so that $AF_{obs} \approx AF_{pred}$. But with increasing percentage of shallow versus whole lake surface areas, the discrepancy between the AFs increases so that $AF_{obs} \ll AF_{pred}$ in polymictic lakes. This occurs because shallow eutrophic lake sediments often exhibit narrow anoxic layers that are not measured by routine DO profile monitoring (Nürnberg 2009; Smith et al. 2011). For the lakes, in which hypolimnetic TP accumulation values were available, IP_{obs} was divided by AF_{obs} to obtain anoxic release rates in the stratifying areas (mg P m^{-2} d^{-1}). We did so to see how RR_{obs} compared with RR_{pred}, as two lakes of very similar P concentration yet fall into adjacent trophic categories might have been assigned markedly different release rates.

The differences between IP_{obs} and IP_{pred} (and contributing variables including AF_{obs} vs AF_{pred}, and RR_{obs} vs RR_{pred}) in stratifying lakes ($n = 42$) were analysed with paired *t* tests. Correlations between corresponding variables were described with Pearson correlation coefficients. The relationships of the key water quality variables with IP_{obs} and IP_{pred} were analyzed. For that purpose, we used data for 19 stratifying Finnish lakes, as they had the complete set of potentially-dependent water quality variables (Finnish Environment Institute). Studied water quality variables included total phosphorus (TP_{surf}, TP_{bot}) and soluble reactive phosphorus concentration (SRP_{surf}, SRP_{bot}) in the surface and in near-bottom water layer (0.5 m above the lake bottom) and concentration of chlorophyll *a*. Means of the whole growing season for the long-term period (1984–2014) were used.

Additionally, we studied the relationships of IP_{obs} and IP_{pred} with IP_{tot}, the total flux of sedimentary P. This internal P loading due to a sum of factors including sediment anoxia was calculated as a function of the difference in phosphorus retentions (Tammeorg et al. 2017). IP_{tot} was demonstrated to affect surface water quality (Tammeorg et al. 2017). Since seven lakes were (continuously or periodically) subject to aeration, we suggested possible implications and thus differentiated two treatments (aerated and non-aerated) while analysing relationships between IP and water quality variables. Analysis of variance was used to test whether there were significant differences between the treatments in the effect of IP_{obs} and IP_{pred} on water quality variables, and IP_{tot}. Log- or square-root-transformations of the studied variables were used to ensure the normal distribution of residuals (by Shapiro–Wilk test).

A tool for predicting internal phosphorus loading due to sediment anoxia and potential linkage to aeration effects

To ascertain lake characteristics responsible for the IP_{pred}, a principal component analysis (PCA) was carried out. Data for all 45 lakes having a complete set of lake characteristics were used. Principal components (PCs) were obtained as weighted linear combinations of the original variables. Original variables included the lake characteristics that were demonstrated to be of high importance for controlling lake phosphorus dynamics, i.e. maximum depth (D_{max}), mean depth (D), lake area (LA), catchment area (CA), external loading of P (IF). Each characteristic was statistically standardized to have a zero mean and unit standard deviation in the set of all lakes. This approach generates principal components (PCs) as new complex (synthetic) uncorrelated factors that integrate individual characteristics. Three lakes behaved as outliers due to exceptionally large IF (Lake Pepin), LA (Lake Erie), and D, D_{max} (Lake Constance), and thus were excluded from the analysis. The effects of the PCs on the IP_{pred} were estimated by using the general multiparametrical linear model. Initially, all five PCs were used together as predictors of the IP_{pred} to ascertain significant PCs. After that, significant PCs were used singly as the predictors of the IP_{pred}. The same approach has been used to describe spatial variability in IP_{obs} (Tammeorg et al. 2017). The rationale for this approach is that variations in sediment P release can hardly be explained by any single lake characteristics (e.g., lake depth), as these often correlate to each other. Data on these lake characteristics are usually more easily accessed for predicting internal P loading, as opposed to, for example, sediment data that require much more effort and expense to collect.

Finally, we demonstrated the potential application of the dependence of IP_{pred} on a specific PC to lake management practice. For that, we calculated the PC values that were driving IP_{pred} for several lakes, of well-documented case studies of aeration treatment on water quality of Gächter and Wehrli (1998), Nürnberg et al. (2003), Schauser and Chorus (2007), Moore et al. (2012) and Kuha et al. (2016). These included Lake Jyväsjärvi (Finland), Lake Sempach (Switzerland), Lake Tegel (Germany), Lake Newman (USA) and Lake Wilcox (Canada). PC values for these lakes were calculated as a sum of products of the coefficients of the IP_{pred}-driving-PC and standardized values of the corresponding lake characteristics. For standardization, mean values and standard deviations of the whole dataset were used. We assumed that variations in the effect of aeration treatment on lake water quality could be coupled to changes in IP_{pred} values along with the IP_{pred}-driving PC. Aeration was considered to be successful when it resulted in reduced concentrations of TP_{surf} and Chl *a*.

Results

Internal phosphorus loading due to sediment anoxia and its contribution to lake water quality

In stratifying lakes of the current study, IP_{pred} varied from 0 to 2117 mg P m^{-2} $summer^{-1}$ (mean 404 mg P m^{-2} sum^{-1}). IP_{obs} was significantly lower (paired *t* test, $p < 0.001$; mean 197 mg P m^{-2} sum^{-1}) and varied from 3 to 1578 mg P m^{-2} sum^{-1}. However, IP_{pred} correlated well with IP_{obs} ($r = 0.645$, $p < 0.001$). AF_{pred} values ranged from 4.9 and 82.7 day sum^{-1} (mean 37 day sum^{-1}) and AF_{obs} from 1 to 72 day sum^{-1} (mean 24 day sum^{-1}). The differences between the AF_{pred} and AF_{obs} values were statistically significant ($p = 0.004$). Release rates of P calculated from the in-lake observations (in situ P increases) increased across the trophic gradient ($p = 0.009$), being on average (± standard error) 1.26 ± 0.17, 3.71 ± 1.06, 11.88 ± 3.30, and 12.84 ± 3.24 mg m^{-2} d^{-1} for oligotrophic ($n = 8$), mesotrophic ($n = 15$), eutrophic ($n = 12$), and hypertrophic ($n = 4$) lakes, respectively. Despite the observed minor overlap for eutrophic and hypertrophic lakes, the values were in the same range as the values that were used in the calculation of IP_{pred} (i.e., release rates of P under anoxic conditions reported in literature for the lakes worldwide; Nürnberg 1997), underlining the importance of trophy for anoxic release of P.

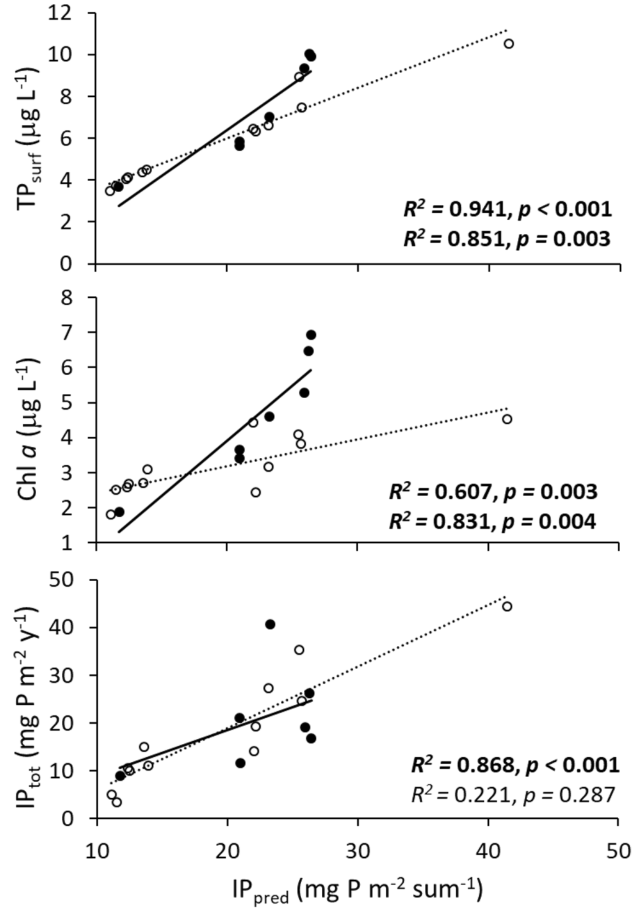

Fig. 1 The concentration of the total phosphorus in the surface water layer (TP_{surf}), chlorophyll *a* (Chl *a*) and total sedimentary P flux (IP_{tot}) as a function of the internal P loading due to sediment anoxia from both deep and shallow areas (IP_{pred}) in non-aerated (open circles) and aerated (filled circles) lakes. Trends are shown for non-aerated lakes (upper r and p values, dashed line) and for aerated lakes (solid line). Note that square-root-transformed values for all variables are presented

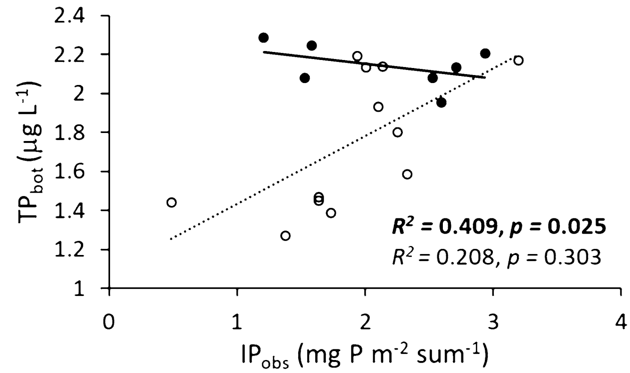

Fig. 2 The concentration of the total phosphorus in the bottom water layer (TP_{bot}) as a function of the internal P loading due to sediment anoxia from deep areas (IP_{obs}) in non-aerated (open circles) and aerated (filled circles) lakes. Trends are shown for non-aerated lakes (upper r and p values, dashed line) and for aerated lakes (solid line). Log-transformed values are presented

In Finnish stratifying lakes, all studied water quality variables and IP_{tot} related significantly and positively to IP_{pred} (TP_{surf}, TP_{bot}, Chl *a*, and IP_{tot}, $p < 0.001$; SRP_{surf}, $p = 0.017$; SRP_{bot}, $p = 0.032$). All these relationships were also significant for a subset of non-aerated lakes, IP_{pred} with TP_{bot} ($p < 0.001$), TP_{surf} ($p < 0.001$), SRP_{surf} ($p = 0.002$), SRP_{bot} ($p = 0.001$), Chl *a* ($p = 0.003$; Fig. 1) and IP_{tot} ($p < 0.001$; Fig. 1). In contrast, for aerated lakes IP_{pred} was only significant for TP_{surf} ($p = 0.003$) and Chl *a* ($p = 0.004$; Fig. 2). Moreover, the correlation of IP_{pred} with Chl *a* was affected by treatment (aerated or not, $p = 0.001$), being higher in aerated lakes. IP_{obs} related significantly only to TP_{bot} ($p < 0.009$). Moreover, the relationship between TP_{bot} and IP_{obs} was still significant ($p = 0.025$) in non-aerated lakes, while not significant in aerated lakes (Fig. 2). Noteworthy, there was no significant difference (*t* test) in the values of IP_{pred} and IP_{obs} between aerated (517 and 314 mg P m^{-2} sum^{-1}) and non-aerated (457 and 216 mg P m^{-2} sum^{-1}) lakes, possibly suggesting similarity in morphology of those lakes.

Spatial variability in internal P loading due to sediment anoxia, potential linkage to aeration

The first three PCs represented about 96% of lake data variability in total (Table 2), whereby 39%, 38% and 18% of the lake variability were explained by PC1, PC2, and PC3, respectively. PC1 separates all the lakes along an axis largely based on lake and catchment size (Table 2). The second orthogonal axis, PC2, further separates all the lakes along

Table 2 Coefficients for calculating the five principal components (PCs) and corresponding eigenvalues of the correlation matrix calculated for 43 lakes with a full set of all eight contributing characteristics. The characteristics needed include: maximum depth (D_{max}), lake area (LA), catchment area (CA), mean depth (D), external loading of P (IF)

Lake characteristics	PC1	PC2	PC3	PC4	PC5
D	0.353	0.577	0.267	− 0.462	0.558
D_{max}	0.289	0.636	0.000	0.442	0.558
CA	0.563	− 0.387	0.218	− 0.480	0.505
LA	0.617	− 0.321	0.000	0.577	− 0.420
IF	− 0.305	0.000	0.933	0.164	0.000
Eigenvalue	1.936	1.921	0.919	0.117	0.107
Proportion of variability	0.387	0.384	0.184	0.023	0.021
Cumulative proportion	0.387	0.772	0.955	0.979	1.000

an axis largely based on mean and maximum depth. The third axis separates the lakes based primarily on external P loading. Of the five PCs only PC3 was found to have significant effect on IP_{pred} ($p<0.001$), and there was a marginal effect of PC2 on IP_{pred} ($p=0.083$). When PCs were used as predictors in the simple linear model, only the effect of PC3 on IP_{pred} remained significant ($R^2=0.345$, $p<0.001$, Fig. 3), though this component explains only a small amount of the variability among the lakes (18%). IP_{pred} increased gradually with an increase in the value of PC3 (Fig. 3).

Three of five well-studied aeration-treated lakes (Jyväsjärvi, Sempach, Newman) had PC3 values similar to values for the lakes of the current study (Table 3). Lake Sempach had the highest PC3 value and Lake Newman, for which positive changes in lake water quality were reported, was characterized by the lowest value of PC3. Exceptionally high values of PC3 were ascribed to Lake Tegel and Lake Wilcox due to the large contribution of external P loading.

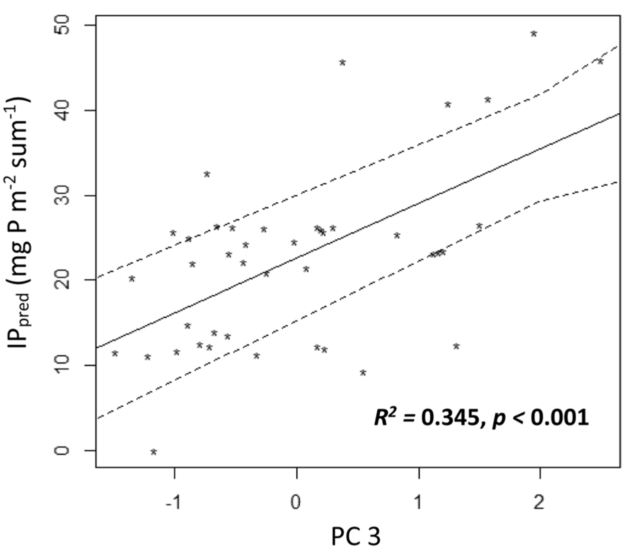

Fig. 3 Dependence of the predicted internal phosphorus loading due to anoxia (IP_{pred}, square-root-transformed values) on the specific combination of lake characteristics represented by PC3 that is governed mainly by external P loading

Discussion

Internal phosphorus loading due to sediment anoxia: importance of shallow areas

Higher values of IP_{pred} than IP_{obs} agreed with the similar trend in AF, where AF_{pred} was also higher than AF_{obs}. These findings were expected, because AF_{pred} and IP_{pred} account for larger sediment areas of P release that are not considered in the observed variables (AF_{obs} and IP_{obs}). A possible source of uncertainty associated with calculations of IP_{pred} can be an assumption that it is mainly trophic state that determines release rate of P under anoxic conditions of sediments in a lake as a whole. Release rates of P may be spatially variable due to sediment heterogeneity with respect to P concentration, temperature and general chemistry (Hilton et al. 1986; Blais and Kalff 1995). Nevertheless, the approach used to quantify IP_{pred} has been shown to result in estimates similar to those by other methods in shallow (mixed) lakes (Nürnberg 1987, 2005; Nürnberg et al. 2013b).

Given that IP_{pred} was associated with the anoxic surfaces of the entire lake basin and IP_{obs} with those of the stratifying lake areas only, the contribution of the P release from shallow areas was 51%, i.e. virtually as high as the input of deep areas (49%). Moreover, results from Finnish lakes demonstrated that the role of shallow areas to internal P loading due to sediment anoxia is of key importance in the control of lake water quality. While IP_{obs} affected only TP_{bot}, IP_{pred}

Table 3 Case studies of aeration treated lakes with implications for water quality

Lake	Type	PC3 value	Effects reported, un (−)/success (+)[b]
Jyväsjärvi	Hypolimnetic oxygenation	0.87	(−) Increased concentration of dissolved oxygen (DO), but no changes in trophic status (based on Chl *a*, TP concentrations)
Newman[a]	Hypolimnetic aeration	− 0.55	(+) Increased DO, reduced internal P loading, decreased biomass of cyanobacteria
Tegel	Hypolimnetic aeration	8.32	(−) No effect on P reduction due to high sedimentation rates, no effect on redox-sensitive adsorption of iron, no effect on phytoplankton or cyanobacteria
Sempach	Hypolimnetic aeration	1.76	(−) Increased DO, no change in P release due to high sedimentation rates and sed/water interface remaining anoxic, increased biomass of cyanobacteria
Wilcox	Hypolimnetic oxygenation, aeration and destratification	8.41	(−) No changes in anoxia, higher summer and fall average concentrations of TP and SRP in the epilimnion, also all measures of cyanobacteria and phytoplankton during treatment years (hypolimnetic aeration/oxygenation). High cyanobacteria biomass was partially due to mixing metalimnetic *Planktothrix* in fall and winter 1998 (Nürnberg et al. 2003)

[a]In Lake Newman, a chemical treatment was also applied

[b]Data for the lakes except Wilcox (Nürnberg et al. 2003) and Jyväsjärvi (Kuha et al. 2016) were summarized by Bormans et al. (2016)

accounting also for the shallow areas affected all of the studied water quality variables, including those of the surface water layer (TP_{surf}, SRP_{surf}, Chl *a*) that are principally important from lake water management perspective. Although thermocline erosion and entrainment of hypolimnetic P-rich water into the epilimnion can occur in lakes with less stable thermoclines (e.g., Nürnberg 1985), P released from anoxic sediments often remains entrapped in the bottom layer during most of the growing season (Marsden 1989). As a rule, it reaches surface water layer too late in the growing season, i.e. at a time when light and temperature limit algal growth (Tammeorg et al. 2017). In contrast, a continuous mixing and contact of sediment with the overlying water column ensures P availability for the algal growth in shallow polymictic lakes and in the shallow areas of stratified lakes. Furthermore, it is very likely that considerable implications for surface water quality are achieved through complex interactions of P release from anoxic sediment with other mechanisms including those of aerobic release in shallow areas. For example, sediment resuspension may considerably promote the release of P also from anoxic sediment by increasing the P concentration gradient between the sediment and overlying water column and by mixing P enriched pore-water into the overlying water (Reddy et al. 1996; Tammeorg et al. 2016). The importance of other mechanisms, like ligand-exchange reactions, desorption from sediment particles, bioturbation cannot be ignored (Holmroos et al. 2009; Niemistö et al. 2012; Tammeorg et al. 2015). In support of our findings, the importance of IP_{pred} for water quality was comparable with that of IP_{tot} that was found to correlate positively with the concentrations of SRP, TP in the surface and bottom water layer and concentration of Chl *a* (Tammeorg et al. 2017). Additionally, Finnish lakes in the current study showed significant positive relationships of IP_{pred} with IP_{tot} that was shown to originate mainly from shallow areas (Tammeorg et al. 2017).

Conclusions about the aeration treatment are limited, because of the relatively small number of treatments in the set of Finnish lakes. Further, our approach (simply creating two treatments based on being aerated or not) has limitations, as each of those cases of aeration is different in terms of methods applied, duration of aeration, and lake characteristics. For example, Lake Tuusulanjärvi has been aerated substantially longer than other lakes. Moreover, destratification (intentionally applied in Tuusulanjärvi) affects nutrient cycling in a different way compared with lakes where hypolimnetic aeration is applied (Cooke et al. 2005; Visser et al. 2016). Hence, it may be an oversimplification to attribute the different relationships of IP_{pred} with the water quality variables just to a treatment effect. However, similar trends of relationships of IP_{pred} with TP_{surf} and Chl *a* for non-aerated and aerated lakes suggest little importance of the aeration-treatment for water quality. This is supported at least by the findings from Enonselkä and Tuusulanjärvi, in which aeration history has had the longest record. Although different techniques (destratification and hypolimnetic aeration) implied different impact mechanisms, no effects for the surface water quality due to aeration were reported for these two lakes. In Enonselkä, aeration has decreased SRP_{bot} and TP_{bot}, but not Chl *a*. Hypolimnetic aeration decreased water column stability (apparent as increases of the hypolimnetic water temperature), resulting in increased sediment resuspension indicated by increased rates of gross sedimentation, and increased TP flux from sediments during the open-water period (Niemistö et al. 2016). Though applied intentionally, artificial destratification in Tuusulanjärvi increased near-bottom water temperature and turbulence that most likely enhanced P recycling (Horppila et al. 2017), similarly to what was observed in Enonselkä. Hence, in both cases aeration supported the supply of P for algal growth by facilitating P transport from shallow sediment areas, an important source of P generated by sediment anoxia. These mechanisms could possibly also explain, why we observed more pronounced relationships of IP_{pred} with Chl *a* in aerated compared to non-aerated lakes.

Implications for lake water management by aeration treatment

It is of crucial importance to consider also P generated by sediment anoxia of shallow areas in comprehensive models, as these areas are of high importance in water quality management and may affect the efficiency of aeration in stratifying lakes. Thus, determining factors behind the variation of IP_{pred} rather than IP_{obs} could be more useful for water quality management. In the current study, we found that IP_{pred} is driven by PC3, a specific combination of five lake characteristics. Given the importance of sediment characteristics (Hupfer and Lewandowski 2008; Randall et al. 2019), incorporating specific fractions (e.g., fractions that are commonly associated with the sediment P release, Fe content, Nürnberg 1988) may further increase the predictive power of the current model. Nevertheless, its current R^2 value was generally in a range of those that are reported for the models predicting release rates of P and internal P loading (Nürnberg et al. 1986; Nürnberg 1988; Carter and Dzialowski 2012; Tammeorg et al. 2017).

In PC3, external P loading (IF) is clearly the major constituent. In general, high IF results in the increased deposition of newly-produced P-rich material (Marsden 1989; Carey and Rydin 2011). High levels of external loading often lead to oxygen deficits that sustain the recycling of P to the water column (Gächter and Wehrli 1998; Moosmann et al. 2006) through the breakdown of the iron-phosphorus complexes (Mortimer 1941, 1942). Both sediment release of P and oxygen depletion have been emphasized to be inevitable phenomena of high trophic state (Gächter and Wehrli 1998; Moosmann et al. 2006; Hupfer and Lewandowski 2008). Noteworthy, recent external load abatement is followed often by an increase in internal P loading (Sas 1990; Jeppesen et al. 2005; Søndergaard et al. 2013). Further, historical external supply of P still contributes to "legacy internal P loading" in the sediment even after IF abatement, and can be a P source for a long time (Jarvie et al. 2013; Sharpley et al. 2013).

Paradoxically, one of the most common reasons for the unsuccessful aeration projects was the insufficient control of the external P loading (Cooke et al. 2005; Bormans et al. 2016). Lake Tegel and Lake Wilcox had the greatest PC3 values, which suggests most pronounced water quality implications of the internal P loading due to sediment anoxia. No positive effect of aeration on P retention was observed in Lake Tegel, in which the improvement in lake water quality was attributed to reduced external load (Schauser and Chorus 2007). Similarly, the first priority of the external load control was emphasized for Lake Wilcox. In this lake, there was no decrease in anoxia. However, reduction in the temperature differences of the hypolimnion and epilimnion due to aeration favoured the upward transport of nutrients resulting in a TP increase in the epilimnion and a reduction in the hypolimnion (no significant change in the water-column averaged concentration; Nürnberg et al. 2003). Both Lake Tegel and Lake Wilcox had a PC3 value that was out of the range of the model produced with the lakes of the current study, and thus the predictions of the corresponding internal P load and its effects should be done with caution. However, Gächter and Wehrli (1998) observed no effect on P cycling in Lake Sempach, which was described by a lower value of PC3 than Lake Tegel and Lake Wilcox, despite the considerable increase in the hypolimnetic DO concentration. The authors explained the phenomenon by no cause and effect relationship between hypolimnetic oxygen deficits and P release, as both are inevitable in case of high trophy (Gächter and Wehrli 1998). Moreover, no additional value of aeration to the effect of external loading reduction was stressed for Jyväsjärvi (Kuha et al. 2016) even though Jyväsjärvi had a considerably lower value of PC3 (PC3 = 0.87). In this lake, aeration triggered changes in the dissolved oxygen (DO) concentration in summer and winter, though these changes did not affect the trophic state of the lake. The improvements in water quality (much lower whole lake TP concentration, associated decrease of average and maximum annual phytoplankton biovolumes, elimination of considerable cyanobacteria blooms) were largely attributed to the aeration in Lake Newman (Moore et al. 2012), which had the lowest PC3 value (PC3 = − 0.55) of the reported lakes. However, hypolimnetic oxygenation was applied concurrently with a chemical treatment (i.e., microfloc alum injection). Moreover, external load controls were also included as restoration activities in Lake Newman, which seem to be a more convincing explanation for lake water quality improvement. Hence, in lakes that have PC3 value around − 0.6, the external P loading is not likely too high to cancel impacts of aeration treatments. Moreover, observations from well-known case studies on aeration support the concept based on our results, and sediment P release is closely linked to external P loading.

Indeed, not many studies report any effects of aeration on surface water. Moreover, there is only a limited number of lakes where aeration was successful (in terms of reduction of algal/and cyanobacterial biomass or Chl *a* concentration). For some lakes that have displayed a positive response to the treatment (Lake Amisk in Canada, Lake Serraia in Italy, Black Lake in the USA) and thus would potentially be insightful in determining the target value of PC3, data on the external P loading are not available. The examples we analyzed suggested higher potential for success of aeration treatments for lakes with PC3 values around − 0.6 (i.e., comparable to that in Lake Newman), while in lakes with PC3 values about 0.9 (like in Lake Jyväsjärvi) external P loading may already abate effects of aeration. By that, we demonstrated the possible importance of the dependence of IP_{pred} on PC3 from lake water quality management perspective.

Conclusions

In stratifying lakes, the contribution of shallow areas to the internal P loading due to sediment anoxia is comparable to that of deep areas. The results from Finnish lakes demonstrated that this contribution is of key importance for water quality and may affect the effectiveness of aeration as a restoration measure. IP_{pred}, internal P loading due to sediment anoxia of both deep and shallow areas, was found to be dependent on the specific combination of lake characteristics PC3, driven mainly by external P loading. By linking this dependence with some case studies of the aeration treatment, we suggest higher potential for success of aeration in lakes with PC3 values around − 0.6.

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