The actual role of oxygen deficit in the linkage of the water quality and benthic phosphorus release: Potential implications for lake restoration

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HIGHLIGHTS

- P release due to anoxia was separated from the total benthic flux of P.
- Regressions of anoxic and total benthic P fluxes with water quality were studied.
- Anoxia has a minor role in water quality control via benthic P release.
- Lake water quality is mainly controlled by P release from shallow areas.
- Results suggest limitations for the use of aeration in lake restoration.

GRAPHICAL ABSTRACT
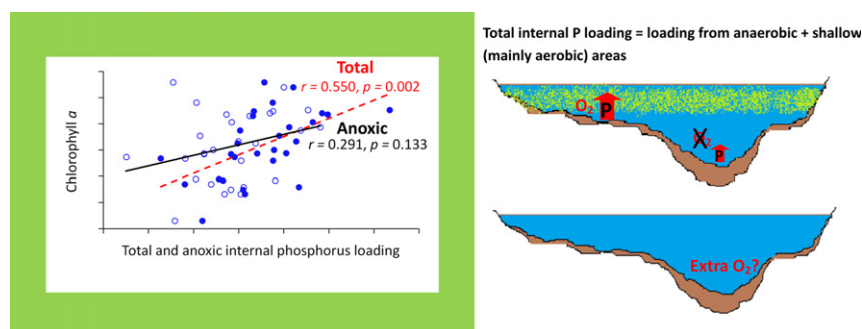
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ABSTRACT

Human activities in watersheds have resulted in huge accumulations of phosphorus (P) in sediments that have subsequently hindered restoration efforts of lake water quality managers worldwide. Much controversy exists about the factors that control the release of P from sediments (internal P loading). One of the main debates concerns the role of oxygen deficit (anoxia) in the regulation of water quality. Our results based on a comprehensive set of lakes worldwide demonstrate that internal P loading (IP_{tot}) plays a significant role in water quality regulation. Internal P loading due to anoxia (IP_{anox}) contributes significantly to the IP_{tot}. However, this contribution is insufficient to significantly increase the chlorophyll a (Chl a) concentration in stratifying lakes. In the lakes of the north temperate and boreal zone, this is because the IP_{anox} reaches surface water layer in the end of the growing season. Observed water quality implications of IP_{tot} are most likely caused by the sedimentary P that actually originates from the shallow areas. These findings suggest limitations for the use of aeration (improvement of the oxygen conditions in the hypolimnion) in lake water quality restoration. Moreover, lake ecosystem managers can benefit from our model that enables to predict anoxia triggered sedimentary P release from the combination of lake characteristics. The final decision on the use of aeration is indeed unique to each lake, and lake specific targets should be considered.

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1. Introduction

Human activities in watersheds have degraded water quality worldwide. Degradation is also likely to be sustained in the years that follow the reduction in nutrient loading from human sources due to the release

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of phosphorus (P) from "legacy P" stores (Sas, 1990; Jeppesen et al., 2005; Schindler, 2012; Jarvie et al., 2013). The water quality improvements cannot be achieved before a scientific consensus is reached on the factors that control the release of P from lake sediments.

The importance of "self-fertilization" for the lakes was recognised as early as the 1900s (Kolkwitz, 1909). The experiments conducted in the 1940s demonstrated that the release of P from sediments occurs under anoxic conditions due to the reduction of iron (III) to iron (II) with a subsequent dissolution of P (Einsele, 1936; Mortimer, 1941, 1942). Following this, hypolimnetic aeration was introduced as a measure in lake water management to counteract hypolimnetic anoxia and associated water quality problems (Mercier and Gay, 1949). Efforts in lake quality management increased in the 1960s and the 1970s (Müller et al., 2012). However, approaches that aimed at increasing oxygen concentration in the hypolimnion (hereafter termed "aeration") often failed to give the expected success. Moreover, the release of P has also been observed to occur under aerobic conditions (Marsden, 1989). A number of other arguments that support the revision of the long-lasting paradigm about the governing role of anoxia in lake P cycling were summarized in 2008 (Hupfer and Lewandowski, 2008). Nevertheless, aeration still remains one of the major methods of lake restoration worldwide (Bormans et al., 2016). In Finland alone, about 100 lakes are currently undergoing aeration treatment to mitigate the anoxia-induced problems via the release of P from sediments (Cooke et al., 2005). There is however still a lack of robust quantitative evidence on the role of anoxia in regulating lake water quality, which is required to affect decision-making policy.

To compensate for this gap in knowledge, we have distinguished between the total internal P loading (IP_{tot}) and the internal P loading due to anoxia (IP_{anox}) for a representative sample of lakes worldwide by compiling data obtained during sampling campaigns in Finnish lakes and data published in literature (i.e. reported lakes). The lakes studied fall to the category of the lakes that are usually aerated. The mean depth for the considerable number of world lakes receiving hypolimnetic aeration reviewed by Cooke et al. (2005) is 11.1 m. The mean depth for the stratifying lakes in our data set was 11.5 m. The general failure of the aeration projects in such lakes makes them particularly suitable for the objectives of our study: 1) to elucidate the role of oxygen deficits in water quality regulation; 2) to identify the potential candidates for aeration. We studied correlations of the water column total phosphorus (TP), soluble reactive phosphorus (SRP), chlorophyll a (Chl a) concentrations, and the IP_{tot} with the IP_{anox} to reveal the role of anoxia in the lake water quality regulation. We stressed the impacts of anoxia for the surface water layer that is particularly relevant from the management perspective, which usually aims at reducing the production of algal biomass (Visser et al., 2016).

2. Methods

2.1. Study area

The lakes that were sampled for the present study (Table S1, lakes nr 1–28) are located predominantly in southern Finland. The area of the lakes ranges from 0.25 to 155 km^2. The mean depth of these lakes varied from 1.1 to 21 m. The majority of the lakes have deep areas, which undergo periodic anoxia, generally in winter and in summer. The trophic status of the lakes ranged from mesotrophic to hypereutrophic (HERTTA Database, 2015). The catchments of the eutrophic and hypereutrophic lakes have been impacted mainly by agricultural activities (HERTTA Database, 2015). All of these lakes were subjected to many attempts of restoration during the past 20 years. Samples were collected also from the three basins of the shallow productive Lake Peipsi (Lake Peipsi sensu stricto, Lake Lämmijärv and Lake Pihkva), which is located on the border between Estonia and Russia. Data on the rest of the lakes used in this study were obtained from literature (defined as "reported lakes"). Hence, our highly representative set of lakes included

those from small to large, shallow to deep and oligotrophic to highly eutrophic. Moreover, our stratifying lakes are representative of those lakes that are usually aerated worldwide (Cooke et al., 2005).

2.2. Internal phosphorus loading from anoxic areas

The internal P load from anoxic areas (IP_{anox}, mg m^{-2} y^{-1}) in lakes with anoxic hypolimnia was calculated using the equation (Nürnberg, 1984):

$$IP_{anox} = \text{anoxic area} \times \text{anoxic period} \times \text{P release rate/lake area} \qquad (1)$$

where the anoxic area (m^2) is the sediment surface area that is in contact with anoxic water, anoxic period (in days per year) is the duration of the anoxia, and the P release rate is the rate at which P is released from the anoxic sediments surface (mg m^{-2} d^{-1}). The product of the percentage of anoxic areas and duration of anoxia can be defined as an "anoxic factor" (Nürnberg, 1984).

Periodic sampling of Finnish lake waters in the frames of monitoring during last 10–20 years enabled the determination of the extent of the anoxia during stratification and the calculation of hypolimnetic accumulation of P, which is a good indicator of net release of P from sediments (Nowlin et al., 2005). In the shallow lakes, where no stratification takes place, it was assumed that $IP_{anox} = 0$. For the reported lakes, the release rates from core incubations were used in the quantification of IP_{anox} in case of unavailability of the values for the hypolimnetic accumulation.

2.3. Total internal phosphorus loading

Total internal P loadings in the lakes studied were calculated by comparing theoretical P retention rates (mass balance calculations) with the observed retention rates (dated sediment cores).

Theoretical P retention (R_{pred}, mg P m^{-2} y^{-1}) for a lake was calculated as follows (Hupfer and Lewandowski, 2008):

$$R_{pred} = TP_{in} - TP_{out} \qquad (2)$$

where TP_{in} is the inflow and TP_{out} is the outflow of P. The main body of data for the mass balance calculations (i.e., TP concentrations in the inflow and outflow and water discharges) was obtained from the Hertta databases of the Finnish Environment Institute (HERTTA Database, 2015). Data on TP_{in} and TP_{out} for many of the Finnish lakes studied were available from the reports of the local environmental authorities. River fluxes were calculated mainly using daily water discharge data and monthly measured concentrations. The loading of P from the catchment accounted also for the contribution from non-monitored area ascertained by the areal extrapolation (Ekholm et al., 1997).

Observed P retention (R_{obs}, mg P m^{-2} y^{-1}) was calculated by multiplying the concentration of TP in the sediment layer by the sedimentation rate. Sediment core samples of lakes located in Finland and the three basins of Lake Peipsi between Estonia and Russia were collected with a HTH gravity corer from the deepest site of each lake and thereby targeted the accumulation areas. Each of the cores was sectioned into 0.5 cm slices to a depth of 20 cm to cover the period for which monitoring data were available. All sediment samples (40 samples per lake) were freeze-dried and ground. The TP concentrations from the sediment subsamples were further determined (Lachat autoanalyzer, QuickChem Series 8000) after wet digestion with sulphuric acid and hydrogen peroxide (Milestone Ethos 1600 microwave oven). Sedimentation rates were determined by dating the cores by ^{210}Pb and ^{137}Cs. The analysis was performed at the Liverpool University Environmental Radioactivity Centre. Sub-samples from each core were analyzed for ^{210}Pb, ^{226}Ra, and ^{137}Cs by direct gamma assay using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1987). ^{210}Pb was determined via its gamma emissions