

# Ten Years of Artificial Mixing and Oxygenation: No Effect on the Internal Phosphorus Loading of Two Eutrophic Lakes

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Hypolimnetic aeration was used in conjunction with reductions in phosphorus (P) inputs in order to lower the P concentrations in two eutrophic lakes. Based on more than 10 years of experience with artificial mixing and hypolimnetic oxygenation we conclude that the lakes' internal P cycling was not affected by increased hypolimnetic dissolved oxygen (D.O.) concentrations. We show that irrespective of oxic conditions in the hypolimnion the sediment/water interface remained anoxic due to unchanged high sedimentation rates of organic matter. This may explain why oxygenation did not increase the P retention capacity of the sediment. However, the presented information indicates that, contrary to general assumption, anoxic sediment surface and high P release rates from lake sediments may not be cause-effect related but simply two parallel symptoms of one common cause: excessive organic matter and P sedimentation exhausting the stock of hypolimnetic D.O. and exceeding the P retention capacity of the sediment after diagenesis. Therefore, it is not surprising that fighting one symptom (an anoxic hypolimnion and sediment surface) does not solve the other one (a high P release rate). These findings and considerations based on more than 10 years of experimental experience warrant a reevaluation of the well accepted theoretical management strategy of limiting lake internal P cycling by maintaining an aerobic hypolimnion and sediment surface.

## Introduction

Increasing primary productivity in lakes (eutrophication) causes high phytoplankton biomass often accompanied by unpleasant blooms, low transparency, high settling rates of organic matter, and anoxic hypolimnetic water layers. Such lakes may produce bad odors, when large masses of algae decay at the shore. Fish kills may occur if algae produce toxins or D.O. is depleted in the whole water column after sudden mixing. Vollenweider's report to the OECD (1) laid the cornerstone for the concept of phosphorus (P) limitation of primary production. It was later confirmed by many large-scale experiments in Canada and Europe (e.g., refs 2–5).

Apart from the external P load to lakes, P is also recycled at their sediment/water interface. As Mortimer (6, 7) demonstrated in his classical studies, P release is unimportant as long as the D.O. concentration exceeds 2 mg L<sup>-1</sup> in the

sediment overlying water. At concentrations below 2 mg L<sup>-1</sup>, P previously bound in solid ferric (hydr)oxide is released. Thus, lake internal P fluxes may enhance eutrophication. Combining the concept of P limitation with these findings suggested that the input of air or oxygen into the hypolimnion of lakes could be an efficient method to fight eutrophication in lakes where the lake internal P cycling was an important P source for primary production.

Although numerous short-term experiments described in the literature confirmed that aeration lowered the hypolimnetic P content during summer, some studies (e.g., refs 8–13) indicated that, nevertheless, aeration had no lasting effect on the P content of the treated lakes. In this study we report on a more than 10-year long experiment on oxygenation and artificial mixing of two eutrophic Swiss lakes (Table 1). These long-term time series provide a unique possibility to test the hypothesis that hypolimnetic aeration diminished or even prevented the release of P from sediments and thus contributed to lower the trophic state of lakes.

To maintain the viability of a small-scale commercial fishing industry, Lakes Sempach and Baldegg are annually stocked with hatchery-reared whitefish larvae (*Coregonus* sp.). Because low hypolimnetic D.O. concentrations were thought to be a major reason for impaired embryogenesis, it was hoped that artificial oxygenation might improve the viability of naturally spawned eggs.

## Study Sites and Methods

Lakes Baldegg and Sempach have been intensively studied during the past years (14, 15). Some of these investigations have concentrated on the P cycling (16–18), sedimentation rates (16, 18–21), and fluxes of dissolved substances across the sediment-water interface (16, 22, 23). Table 1 summarizes the major physical and chemical characteristics of the two eutrophic hard water lakes, and Figure 1a presents their geographical location.

The combined aeration/oxygenation technique applied is schematically presented in Figure 1c,d. During winter, pressurized air, produced by a compressor at the shore, is released into the deepest area of lakes to induce and enhance vertical mixing. Hypolimnetic water poor in D.O. is transported to the lake surface where it takes up oxygen from the atmosphere (24). This mode of operation represents a cost-effective way to increase the concentration of D.O. during winter (Table 1). From an ecological point of view, artificial mixing is not feasible during summer, when stratification should be maintained to avoid transport of nutrients from the tropholytic into the trophogenic layer. Therefore, during summer pure oxygen is released into the hypolimnion of the two lakes as very small bubbles that completely dissolve before reaching the thermocline (25). O<sub>2</sub> is taken from shore based storage tanks containing liquid oxygen.

The P cycling of the two lakes was analyzed with the help of the following data sets:

1. Water column data were obtained from monthly monitoring programs sampling the lakes at their deepest sites. These programs were initiated in 1982 and 1984 in Lakes Baldegg and Sempach, respectively. Older data sets with less frequent sampling, dating back to 1950, were also included in our analysis.

2. P-inputs: The annual P load of rivers was estimated from river specific [P]/Q (concentration/water discharge) relationships and continuous water discharge measurements. The [P]/Q relationships were established from spot sampling the rivers every 22 days and additional sampling at high

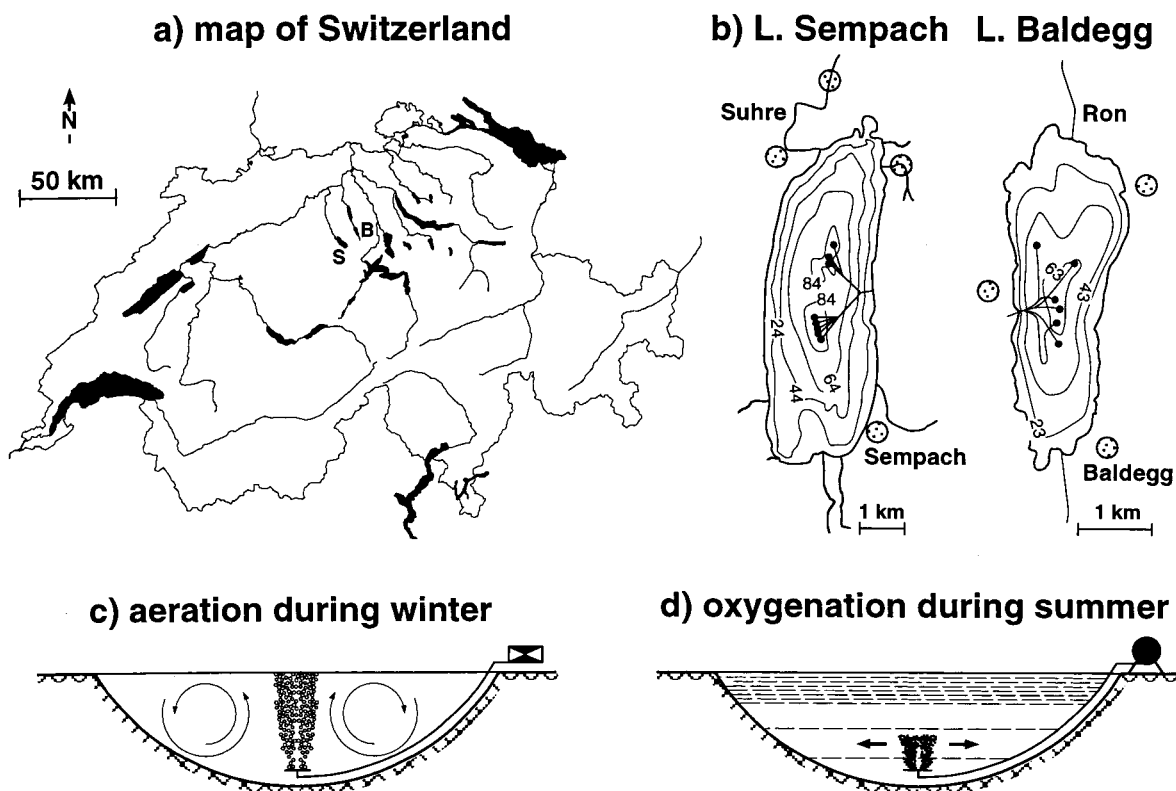
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**TABLE 1. Physical and Chemical Characteristics of Aerated and Nonaerated Lakes Sempach and Baldegg and Technical Information on Aeration and Oxygenation**

	Lake Sempach		Lake Baldegg		ref
Physical Characteristics					
surface area (km <sup>2</sup> )		14.4		5.2	(32)
mean depth (m)		44		33	(32)
maximum depth (m)		87		66	(32)
av flushing rate $\rho_w$ (year <sup>-1</sup> )		0.06		0.13–0.25	(32)
$\beta$ vertical form factor (–)		0.67		0.63	(32)
Chemical Characteristics					
	nonaerated	aerated	nonaerated	aerated	
P concentration at overturn (mg m <sup>-3</sup> )	160		520		(32)
hypolimnetic O <sub>2</sub> consumption (g O <sub>2</sub> m <sup>2</sup> d <sup>-1</sup> )		1.5		1.5	(32)
gross P sedimentation rate K (year <sup>-1</sup> )		0.31		0.46	(a)
maximum bottom [NH <sub>4</sub> ] (mg N m <sup>-3</sup> )	900	50	1500	50	(b)
maximum bottom [CH <sub>4</sub> ] (g m <sup>-3</sup> )	2.4	0	2.6	0.3	(b)
maximum bottom [Fe <sub>tot</sub> ] (mg Fe m <sup>-3</sup> )	50	30	56	20	(b)
maximum bottom [Mn <sub>tot</sub> ] (mg Mn m <sup>-3</sup> )	1000	500	800	230	(b)
maximum bottom [H <sub>2</sub> S] (g m <sup>-3</sup> )	0	0	1	0	(b)
turnover [SO <sub>4</sub> ] (g m <sup>-3</sup> )	11	11	17	16	(b)
Technical Characteristics					
aeration/oxygenation since	1984		1982		(32)
aeration rate (Nm <sup>3</sup> h <sup>-1</sup> )	340		200		(24, 42)
number of aerators	8		3		(32)
operation costs of aeration (CHF kg <sup>-1</sup> O <sub>2</sub> )	0.02		0.01		(24, 42)
oxygenation rate (t O <sub>2</sub> d <sup>-1</sup> )	3		3		(24, 42)
number of diffusers	8		6		(24, 42)
operation costs of oxygenation (CHF kg <sup>-1</sup> O <sub>2</sub> )	0.3		0.3		(24, 42)

<sup>a</sup>  $K = S/[P] \cdot z$ , where S, [P], and z are gross sedimentation (sediment trap measurements (32)), total P concentration, and mean depth, respectively.

<sup>b</sup> Unpublished data supplied by Ernst Butscher, Environmental Protection Agency, Lucerne. Bottom samples were sampled at depths of 85 and 65 m. Concentrations of the nonaerated lakes are typical for the two-year preaeration period.



**FIGURE 1. (a) Location of Lakes Sempach (S) and Baldegg (B); (b) maps with depths contours (in meters) and aerator positions (Rivers Suhre and Ron are outflows); (c) principle of artificial mixing in winter; and (d) oxygenation in summer.**

discharge rates. In addition, direct P inputs into the lakes from sewage treatment plants and from atmospheric deposition were included in these estimations.

3. Sediment mapping: To evaluate the effect of increased D.O. concentration on the P content of the sediment, a

geochemical sediment mapping project with 38 sampling stations was conducted in Lake Baldegg (26).

4. Sediment core analysis: Diagenesis and sediment accumulation of P compounds was investigated in sediment cores sampled at the deepest location in Lake Sempach

TABLE 2. Changes in the Loads of Total P ( $LP_{total}$ ) and Dissolved P ( $LP_{dissolved}$ ) of Lakes Baldegg and Sempach during the Last Decade (tons year<sup>-1</sup>) (32)

Lake Baldegg	$LP_{total}$	$LP_{dissolved}$	Lake Sempach	$LP_{total}$	$LP_{dissolved}$
1958	9.6	7.0	1954	4.4	3.0
1975/1976	13.2	8.4	1976/1977	15.0	11.8
1985/1987	21.1	8.4	1984/1986	14.6	9.1
1987/1990	14.6	6.5	1986/1988	18.7	9.2
1991	11.8	6.0	1987/1990	15.2	7.5
1992	16.9	8.5	1991	13.3	6.9
1993	14.6	7.4	1992	17.6	9.4
1994	18.8	9.8	1993	17.3	9.4
			1994	16.7	8.9

(16–18). In Lake Baldegg a freeze core technique was applied to sample the layered sediment with a yearly resolution for the period 1885–1993 (27).

5. Expected effects of mixing and oxygenation on the P content of Lake Sempach were predicted with a one-box model (24). According to eq 1, changes in the P content of a lake depend on rates of input ( $I$ ), release from sediments ( $R$ ), gross sedimentation ( $S$ ), and output ( $O$ ), where  $V$  is the lake volume and  $[P]$  its average P concentration.

$$V d[P]/dt = I + R - S - O \quad [\text{tons year}^{-1}] \quad (1)$$

If, in a simplified linear approach, output  $O$  and net sedimentation ( $S - R$ ) are modeled as first-order processes with  $\rho$  and  $\sigma$  as rate constants [year<sup>-1</sup>], then the P export via the outflow is

$$O = \beta \rho [P] V \quad [\text{tons year}^{-1}] \quad (2)$$

where the flushing rate  $\rho$  equals the reciprocal water residence time  $\tau$  [year] and  $\beta$  [–] relates the average P concentration in the outflow to the average concentration of the entire lake and P net sedimentation ( $S - R$ ) equals

$$S - R = \sigma [P] V \quad [\text{tons year}^{-1}] \quad (3)$$

If, however,  $[P]$  exceeds a critical concentration  $[P]^{crit}$ , then net sedimentation or permanent P burial rate ( $S - R$ ) does no longer increase linearly with  $[P]$  (28). It rather approaches a constant value  $c$  that likely does not depend on redox conditions at the sediment surface but on the sedimentation of minerals that can precipitate or adsorb P in the anoxic sediment after early diagenesis of the settled organic material. Thus, when gross sedimentation  $S$  exceeds the maximum P retention capacity  $c$ , the excess amount  $R$  is released to the water column, and net P sedimentation becomes independent of the lakes' P concentration.

$$S - R = c \quad \text{for } [P] > [P]^{crit} \quad (4)$$

Sampling, dating, and analysis of sediments was conducted as described previously (16, 21). To measure in situ D.O. profiles across the sediment/water interface we applied the method described by Müller et al. (29).

## Results

**Oxygen.** Artificial mixing during winter and bubbling with oxygen during summer successfully restored oxic conditions throughout the water column in both lakes. Figure 2 depicts concentration maxima and minima observed at their deepest locations. Prior to 1985, Lake Sempach became anoxic at depths exceeding 60 m every summer, and the natural intensity of mixing during winter was not always sufficient to completely restore the D.O. deficit at the lake bottom until next spring. Since 1985, D.O. concentrations rarely dropped below 4 g m<sup>-3</sup>, even at the lake bottom. In Lake Baldegg

natural oxygen replenishment during winter was always insufficient, and during the 1970s the lake was anoxic below 20 m nearly throughout the whole year.

Horizontal gradients in D.O. concentrations were restricted to a distance of less than 5 m from the diffusers (EAWAG, unpublished report). However, it was shown (16) that highly variable but sometimes steep vertical D.O. gradients prevailed in the water layer above the sediment. Thus, very likely at the sediment water interface the D.O. concentrations were lower than shown in Figure 2. However, as shown in Table 1 oxygenation resulted not only in higher D.O. concentrations but also in lower of NH<sub>4</sub>, CH<sub>4</sub>, Mn, and H<sub>2</sub>S concentrations close to the lake bottom. More detailed information on the seasonal and spatial evolution of these solutes in the two lakes prior and after oxygenation has been presented by Stadelmann (30, 31).

**Phosphorus Loading and Concentration Trends.** In the following P balances we consider only the dissolved P loadings, because P associated with allochthonous particles settles quickly and close to the river mouths and does not affect the sedimentation rate, the P burial rate, and the total P concentration of the lakes at the sampling stations relatively remote from the inlets (42). In Lake Sempach, the loading of dissolved P increased from about 3 tons year<sup>-1</sup> (1950) to 12 tons year<sup>-1</sup> (1976/1977) and since then decreased to about 9 tons year<sup>-1</sup> in 1984/1986 (Table 2). Chemical P elimination in sewage treatment plants and the ban of P in detergents (1986) were the key factors for this reduction. As a consequence, the P-content of the lake increased 10-fold from 10 tons (16 mg m<sup>-3</sup>) in 1954 to a maximum value of about 100 tons (160 mg m<sup>-3</sup>) in 1983 but has decreased since then continuously (Figure 3). Due to its high water residence time the P content of Lake Sempach (Table 1) responds only slowly and delayed to changes in its P load.

The load of Lake Baldegg with dissolved P varied since 1975 between 6 and 10 tons year<sup>-1</sup> depending on weather conditions. Because its P content peaked in 1973 and is strongly decreasing since then its P load must have strongly exceeded the mentioned values prior to 1975. However, no reliable information is available.

From sediment trap measurements it is known that gross P sedimentation  $S$  was about 2.2 g m<sup>-2</sup> yr<sup>-1</sup> (average value 1984–1988) and 3.2 g m<sup>-2</sup> yr<sup>-1</sup> (average value 1984–1985) in Lakes Sempach and Baldegg, respectively (32). Sediment investigations indicated however that the respective permanent P burial rates were only 0.6–0.8 g m<sup>-2</sup> yr<sup>-1</sup> (16) and 1 g m<sup>-2</sup> yr<sup>-1</sup> (Figure 3c). From this it follows that about 22 and 11 tons yr<sup>-1</sup>, respectively, must have returned from the sediments of the two lakes. Hence, the internal P loads exceeded the external P-loading considerably in both lakes (Table 2).

The sediment cores retrieved from Lake Baldegg showed three distinct zones: (i) The gray, homogeneous layer at the bottom of the cores was deposited before the onset of eutrophication. (ii) The eutrophic period with an anoxic hypolimnion is reflected in laminated sediments (According

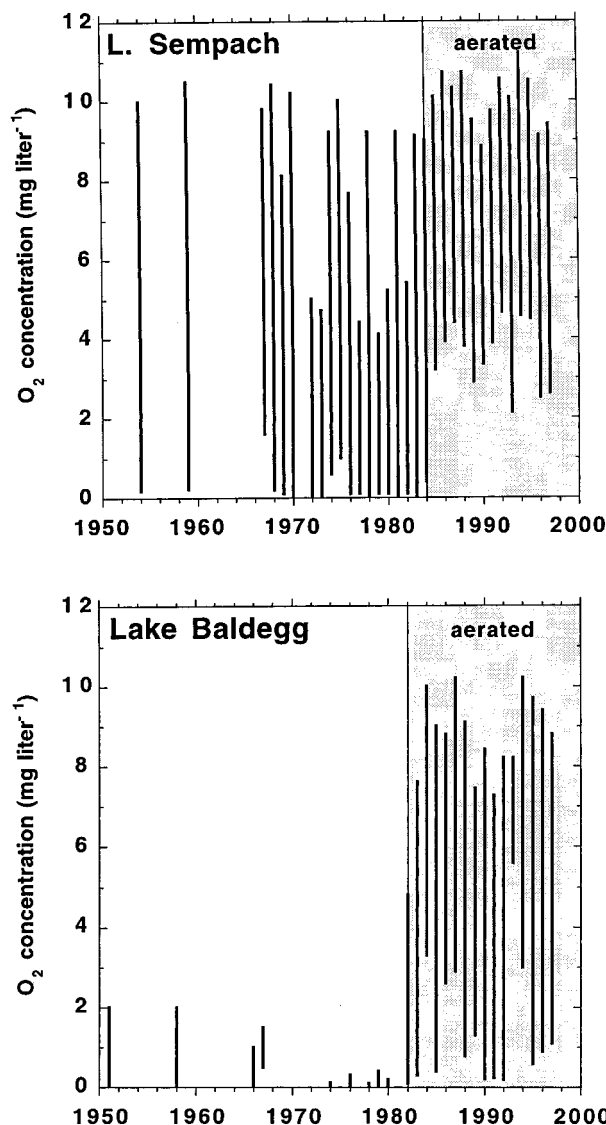


FIGURE 2. Yearly ranges of D.O. concentration close to the bottom of Lakes Sempach (sampling depth 85 m) and Baldegg (sampling depth 65 m), respectively.

to varve counting, the lake became anoxic periodically as early as 1885 at its deepest point and at about 1940 at a depth of 40 m.). (iii) The homogeneous, brownish, some few centimeters thick layer at the top of the cores taken from water depths  $< 55$  m can be related to the recolonization of the sediment by bioturbating chironomids and tubificids (32) in the aerated lake. Geochemical results from the three zones of the 38 cores are summarized in Table 3. Definitely, the average P concentrations of the varved and the most recent bioturbated layer were not significantly different. From this, we conclude that although oxygenation and artificial mixing had visible effects on color and structure of the sediment, it did not affect its P retention. However, the unstructured top layer contained less organic carbon ( $25 \pm 8$  mg C g<sup>-1</sup> dry matter) than the varved layer ( $31 \pm 7$  mg C g<sup>-1</sup> dry matter), indicating that oxygenation accelerated the mineralization of the settled organic matter.

## Discussion

**Effect of Aeration and Oxygenation on P Cycling.** If, as expected, increased hypolimnetic D.O. concentrations would have suppressed the release of P from sediments, then, according to eq 1, the P content of the lakes had responded

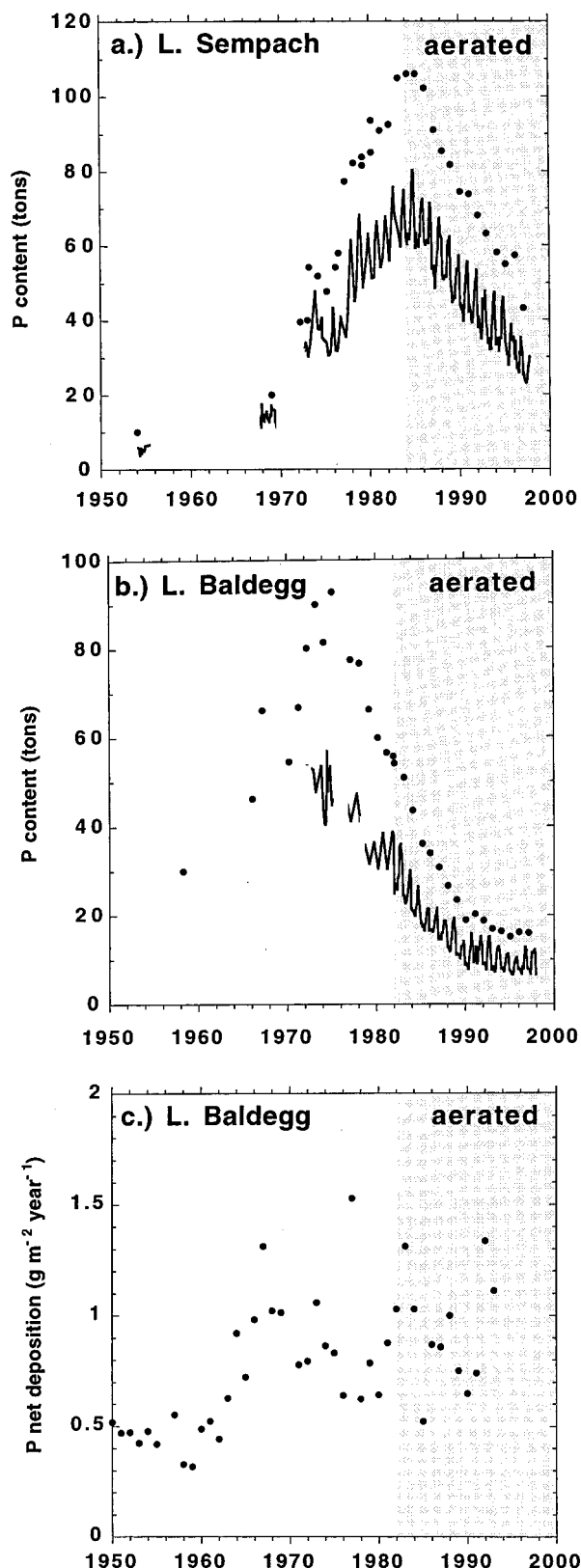


FIGURE 3. Changes in the P content at overturn (dots) and seasonal changes of the hypolimnetic ( $z > 20$  m) P content (lines) in Lakes Sempach (a) and Baldegg (b). Part c shows yearly P deposition rates in Lake Baldegg, derived from freeze core analysis (27).

drastically to aeration and oxygenation. Assuming that the average external loading with dissolved P was 9 tons year<sup>-1</sup> since 1985 and 7 tons year<sup>-1</sup> since 1982 in Lakes Sempach and Baldegg, respectively (Table 2), and that the yearly gross



TABLE 3. Average Concentrations and Standard Deviations of Organic Carbon (POC), Organic Nitrogen (PON), and Phosphorus (P) in Three Sediment Layers Obtained from 38 Cores in Lake Baldegg (32)

layer	condition during deposition	POC (mg g <sup>-1</sup> )	PON (mg g <sup>-1</sup> )	P (mg g <sup>-1</sup> )
brown	aerated	25 ± 8	2.8 ± 1.0	0.82 ± 0.16
laminated	anoxic	31 ± 7	3.3 ± 0.8	0.77 ± 0.16
gray	oxic	22 ± 10	2.2 ± 1.0	0.45 ± 0.10

sedimentation  $S$  and export via the outflow  $O$  can be described by first-order reactions ( $S = 0.31[P]V$ ;  $O = 0.043[P]V$  for Lake Sempach and  $S = 0.46[P]V$ ;  $O = 0.13[P]V$  for Lake Baldegg), Figure 4a,b predicts the development of the P content of the two lakes for two scenarios: (1) after the onset of oxygenation, the release of P from sediments  $R$  was zero (i.e., net sedimentation  $N$  equaled gross sedimentation  $S$ , dashed line) or (2) net sedimentation was unaffected by oxygenation (solid line). In contrary to the model that assumes zero P release from the sediment overlaid with oxic water (dotted lines in Figure 4a,b), in both lakes the model assuming a constant net sedimentation (10 tons year<sup>-1</sup> in Lake Sempach and 6 tons year<sup>-1</sup> in Lake Baldegg) agrees well with the observed data. Taking into account the possible inhomogenities of the sediment, the accuracy, and the year-to-year variability of P load and flushing rate, these sedimentation rates agree surprisingly well with average net deposition rates determined for the preoxygenation period at the deepest location of the two lakes from sediment analysis (about 11 tons year<sup>-1</sup> in Lake Sempach (16), and about 5 tons year<sup>-1</sup> in Lake Baldegg (Figure 3c)). Obviously, oxygenation did not immediately suppress the release of P from the sediments. This conclusion is also supported by the observation that during summer, P continued to accumulate in the hypolimnion of both lakes, regardless of the increased D.O. concentration at the lake bottom (Figure 3a,b). However, hypolimnetic P accumulation showed a decreasing trend with the decreasing total P content and thus, likely, decreasing gross sedimentation of P. These observations agree with the hypothesis that  $R$  approaches zero when  $S$  approaches the P binding capacity  $c$  of the sediment.

Hence, based on more than 10 years of experience with oxygenation of two large and deep lakes, we conclude that (i) the observed decreases in P concentrations of the lakes were solely due to the lowered external loading and (ii) increased D.O. concentrations in the hypolimnion had no effect on the yearly net sedimentation of P. This seems to be in contradiction with numerous experimental observation demonstrating accelerated P release when the sediment overlying water became anoxic.

#### Hypothesis on Binding of P to Ferric (Hydr)oxides.

Figure 5 relates the size of annual sediment layers to a typical D.O. profile measured by microelectrodes. In Lake Baldegg about 1.2 cm of new sediment is deposited each year. Due to compaction the average thickness of the varves decreases to about 0.8 cm within 2 years (21). On the other hand, in situ measurements with oxygen electrodes indicated a thickness of the diffusive boundary layer (DBL) at the submillimeter scale (29). Thus, as illustrated in Figure 5 only a few percent of the uppermost annual sediment layer is in contact with traces of D.O. Below this thin film, available iron oxides are reduced, and previously adsorbed P is released again. According to Fick's first law, the rate of transport of oxygen across the DBL reaches its maximum possible value if the D.O. concentration is zero at the sediment surface. Therefore, if in an aerated eutrophic lake the oxygen demand of the sediment equals or exceeds the maximum possible

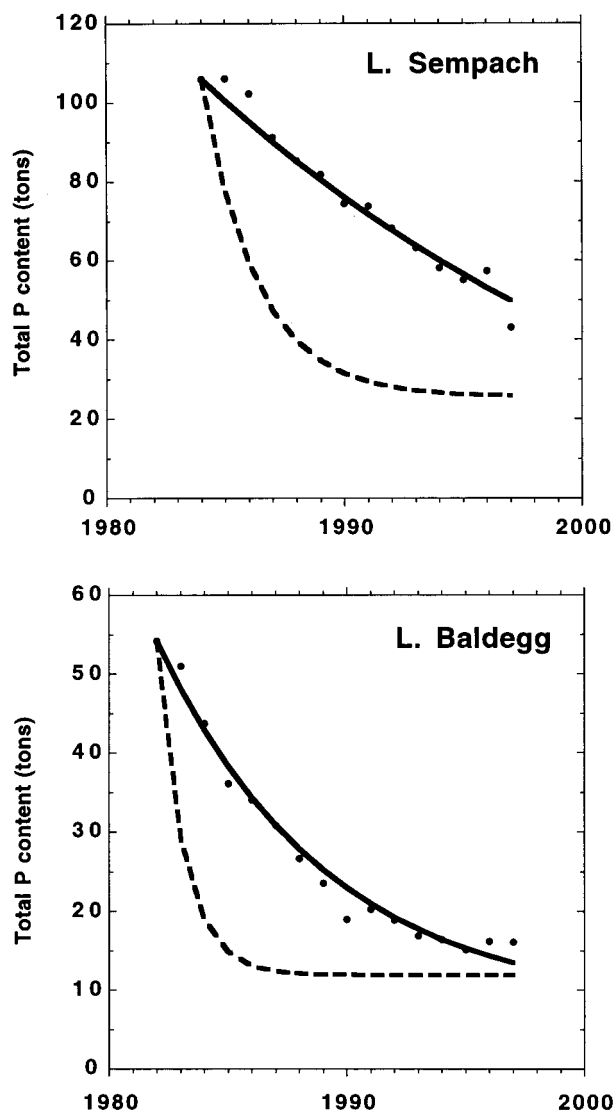


FIGURE 4. Observations (dots) and model (eq 1) predictions (lines) of the total P content on the oxygenated Lakes Sempach and Baldegg: Predictions presented by the solid lines assume a constant net sedimentation (10 tons year<sup>-1</sup> and 6 tons year<sup>-1</sup> in Lakes Sempach and Baldegg, respectively). The dotted lines assume no P release from sediments in the oxygenated lakes. In both cases dissolved P loads and total P export rates are assumed constant, i.e., 9 tons year<sup>-1</sup> and 7 tons year<sup>-1</sup> and 0.31 and 0.46 year<sup>-1</sup> in Lakes Sempach and Baldegg, respectively.

supply, the sediment surface will stay anoxic even if D.O. is present in the overlying water. Hence, an oxic hypolimnion does not necessarily guarantee an oxic sediment surface and thus an increased capacity to retain P.

*Beggiatoa* sp. is a microaerophilic bacterium that oxidizes H<sub>2</sub>S with oxygen as an electron acceptor. Thus, the presence of a dense mat of this bacterium at the sediment surface indicates that, although both H<sub>2</sub>S and oxygen were present within the mat, below the mat the free sulfide likely reduced ferric (hydr)oxides, regardless of the oxic conditions in the overlying water. Sulfide resulting from sulfate reduction favors the precipitation of amorphous FeS and pyrite reducing the availability of iron for P adsorption or (Fe,Mn)<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub> precipitation in anoxic sediments (33–35).

In principle, our observations and conclusions are not in disagreement with the results reported by Mortimer (6, 7). If, as in Mortimer's laboratory experiments, in a eutrophic lake, sedimentation of organic material was stopped and the

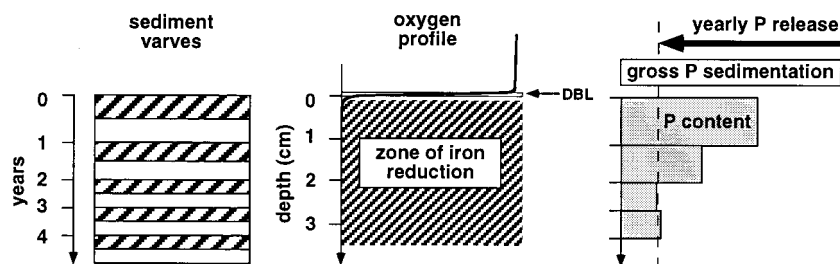


FIGURE 5. Schematic representation of the sediment-water interface in Lake Baldegg, based on varve measurements from in situ freeze cores (27) (left); a typical in situ D.O. profile (29) (center); and yearly gross P sedimentation and P content of yearly sediment layers and resulting yearly P release (right).

hypolimnetic water was kept permanently oxic, then ferric (hydr)oxides would form in the uppermost sediment and trap the P. However, real lakes differ from such hypothetical experiments: Depending on the seasonally variable oxygen demand of the sediment and on the D.O. concentration in the hypolimnion, the sediment surface may stay permanently oxic or transiently become anoxic and then release the previously fixed redox-dependent P (Figure 5). If oxygenation permitted a permanent oxic sediment surface, then it obviously would affect the P cycling of the lake: Ferric (hydr)-oxide may adsorb phosphate, or bacteria may store P in the form of polyphosphate (17) and thus diminish the P release on a seasonal time scale. However, even under such ideal conditions, each oxic sediment surface will eventually be buried by settling material and thereby be reduced sooner or later. At the latest then, it will release again the P additionally retained under oxic conditions. Therefore, even if oxygenation may affect the transitory binding of P in lake sediments, it hardly will affect its permanent binding and hence the trophic state of a lake (28). Thus, in eutrophic lakes the ultimate release of P from sediments seems not to depend on hypolimnetic D.O. concentrations but on the balance between gross P sedimentation and the P retention capacity resulting from early sediment diagenesis in anoxic, iron reducing sediment layers. If, however, anoxic conditions in the hypolimnion and large P release rates are simply two parallel symptoms of one common cause (excessive organic matter sedimentation), then it is not surprising that fighting one symptom (instead of the common cause) does not necessarily solve the other problem.

Hupfer et al. (17) determined in a core taken from Lake Sempach in 1992 the P content of the sediment layer buried 4–5 cm below the sediment surface as  $0.6 \text{ mg P g}^{-1}$  of dry weight. Based on continuous sediment trap observations (16), this material had settled in the years 1985 and 1986. At that time, it had an average P content of 3 mg P per gram of dry weight. Hence during the 5–6 years of diagenesis, the material lost 80% of its initial P content (see Figure 5) although, as shown in Figure 3a, the water overlying the sediment was permanently oxic. After deposition, the sediment loses at first mainly NaOH-NRP, a fraction that includes organic P and polyphosphates. Later during diagenesis, 90% of the BD-P is lost. BD-P is the fraction that includes mainly the P associated with ferric (hydr)oxides (18). Obviously, oxic conditions in the hypolimnetic water cannot prevent reduction of Fe(III) after its burial by younger sediments. As a consequence, the iron (hydr)oxide present at the sediment surface is only a transient (but not a terminal) sink for P. Krajewski et al. (36) suggested that transitory fixation and release of phosphate leading to elevated concentrations of dissolved phosphate in close proximity to the water-sediment interface may enhance the likelihood of apatite deposition. However, according to Hupfer et al. (18) aeration did not effect the composition of solid P species after early diagenesis. Friedl et al. (37) identified  $(\text{Fe,Mn})_3(\text{PO}_4)_2$  as one of the sinks for phosphate in anaerobic sediment

of Lake Sempach. But up to now, no evidence exists that aeration and oxygenation of the lake would enhance the formation of this mineral.

**Effect of Aeration/Oxygenation on the Biota.** Although oxygenation does not permanently lower the P content of a lake, it may provide other advantages. If a formerly anoxic hypolimnion is oxygenated at a sufficient rate, fish and the bottom fauna are able to reinvade and colonize deeper regions (32, 38). However, Ventling-Schwank and Müller (39) demonstrated that over three successive spawning seasons no naturally spawned egg survived to hatching, regardless of high D.O. concentration in the overlying water. They concluded that due to the high oxygen demand of the sediment, the eggs lying on the sediment surface or being buried by settling or resuspended sediment particles (39) suffered from a too low oxygen supply, even if the D.O. concentration in the overlying water exceeded  $7 \text{ mg L}^{-1}$ . Hence, not only too low D.O. concentrations in the water but also the elevated oxygen demand of the sediment seems to be detrimental to naturally spawned eggs. Because oxygenation does not decrease the latter, artificial oxygenation of eutrophic lakes cannot guarantee a successful natural propagation of the commercially interesting whitefish. This agrees with the finding of Müller (41), who showed that successful in situ reproduction is not primarily governed by the hypolimnetic D.O. concentration but by the trophic state of a lake, which likely governs the oxygen demand of the sediment.

To sum up, it is technically possible to artificially maintain oxic conditions in the hypolimnion of eutrophic lakes. In such lakes, fish, zooplankton, and bottom fauna are no longer limited to the oxic epilimnion but may colonize the whole lake volume. However, oxygenation does neither affect mortality of fish eggs at the lake bottom nor the gas bubble disease of fish larvae (39, 40).

**Oxygenation Is No Solution To Fight P Pollution.** As discussed (16, 32) and sketched in Figure 5 oxygenation does not affect the permanent burial of P in the sediment and, thus, has no lasting effect on the trophic state of a lake. Contrary to the general assumption, anoxic hypolimnia and high P release rates from lake sediments may not be cause-effect related but simply two parallel symptoms of one common cause: excessive organic matter sedimentation exhausting the stock of D.O. and high P sedimentation rates exceeding the P retention capacity of the anoxic sediment after diagenesis. If the finite P retention capacity of the lakes sediment is controlled by weathering and erosion processes in the watershed defining the mineral composition of the sediment, it does not surprise that fighting one symptom (anoxic hypolimnion) does not solve the other one (high P release rate). These findings and considerations warrant a reevaluation of the well accepted theoretical management strategy of limiting the lake internal P cycling by maintaining an aerobic hypolimnion and sediment surface and hence lowering its trophic state without lowering its external P loading. They fully agree with observations of Caraco et al.

(35) indicating that the focus on dissolved oxygen as the only controlling mechanism of P release is misplaced and that variables other than oxygen may be of critical importance.

As the more than 10-year long experiments have shown, an artificial system "eutrophic lake with an aerobic hypolimnion" will never become self-maintaining. Therefore, we suggest fighting the cause and waiting for recovery instead of treating a negative symptom forever at very high costs (Table 1). As shown in Figure 3, measures taken to lower the P load have been successful insofar as the P concentration in both lakes decreased significantly. However, Gächter et al. (42, 43) showed that more P is spread as manure to the soil than is removed with the crop. This results in a permanent P enrichment of soil and hence eventually in a further increase of the P load to the lakes. Thus, to achieve a lasting lake recovery, prevention of enrichment or even a depletion of the soils' mobile P content seems to be an irrevocable prerequisite.

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