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Predicting internal phosphorus loading in stratified lakes

By

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Abstract

The ability to predict internal phosphorus loading in stratified lakes has been given new urgency by the realization that traditional best management practices to control external loading have limited effectiveness. We tested the hypothesis that lake sediments with molar Al:Fe ratios greater than 3 would release very little P (Kopáček et al. 2005). We fractionated operationally-defined species of phosphorus, aluminum, and iron in the profundal sediments from a diverse collection of lakes, and sought predictive relationships with previously determined phosphorus release rates from these same sediments. Our results suggest that sediments with Al:Fe molar ratios greater than 3 release negligible amounts P, and that in sediments with Al:Fe ratios less than 3, P release is significantly correlated with the concentrations of reductant-extractible P and the contribution (%) of NaOH-extractible P. We constructed a decision tree model to enable lake managers to anticipate the magnitude of internal P loads in lakes undergoing increased watershed development or changes in thermal stratification and subsequent anoxia due to climate change.

Key Words: Internal P loading, P fractionation, Al:Fe ratio, sediments, eutrophication

Introduction

Forty years ago the late Frank Rigler and his students developed a series of empirical models that would enable limnologists and lake managers to predict the consequences of changes in phosphorus loading in lakes (Dillon and Rigler 1975). Their goal was to predict spring turnover phosphorus concentration and its consequences (summer average chlorophyll, Secchi disk transparency, areal hypolimnetic oxygen deficit, etc.) from readily measured or easily obtainable variables such as lake area, annual discharge, watershed land use, etc. many of which could be extracted from maps without the need for field visits to the lakes. The approach was novel at the time, and its successes spawned a large body of empirical research that enabled the prediction of a variety of lake trophic characteristics (see Peters (1986) for a summary). The ability to predict the consequences of increases or decreases in [P] became the basis for much lake management effort. It allowed the consequences of proposed development, for example, to be estimated in advance, and it allowed more realistic remediation targets to be set for lake restoration. On the whole, the approach has been a remarkable success. However, there have been a number of lakes where decreases in P loading have not resulted in predicted improvement in lake trophic status. Jeppesen et al. (2005) presented the results of phosphorus loading reduction in 35 lakes and concluded that the lake recovery period often exceeded three times lake hydraulic retention time (three retention times are needed to flush 95% of the lake's mass of dissolved P) by an order of magnitude or more. The lingering disparity between predicted and realized trophic state was attributed to the phenomenon of internal P loading from sediments. Further, there have undoubtedly been instances where the consequences of development on P concentrations have far exceeded what was anticipated, again, due to internal loading, although data are conspicuously lacking here since most studies are concerned with lake remediation, rather than degradation.

The phenomenon of internal loading of P from sediments was not fully appreciated at the time Rigler's models were developed. However, once the implications for internal P loading were recognized, several attempts were made to identify the causal mechanisms with the goal of prediction. The paradigm for internal loading of P from the sediments of stratified lakes argues that during periods of anoxia, redox-mediated shifts in the solubility of Fe-bound P species creates a concentration gradient between sediment interstitial water and the overlying hypolimnion. Dissolved P accumulates in the hypolimnetic water mass and is transferred to the epilimnion by diffusion or mixing, or is directly accessed by vertically migrating phytoplankton (James et al. 1992, Gervais et al. 2003, Molot et al.

2014) Consequently, attempts to predict internal loading focused on the concentration of Fe-bound P in the sediments, and the duration of the anoxic period. However, many studies have shown rates of P release are highly variable, even in sediments with high concentrations of Fe-bound P (Nürnberg et al. 1986, Ostrofsky et al. 1989, Prairie et al. 2001), and although the models that have been developed have statistical significance (e. g. , Nürnberg et al. 1986), none has had sufficient predictive power to be useful in predicting the likelihood or the magnitude of internal P loading.

Interest in internal loading has been given a new urgency by the recent evaluation of the ineffectiveness of traditional best management practices (BMPs) such as vegetated shoreline buffers, artificial wetlands, detention basins, etc. A critical meta-analysis of these and other common BMPs (Osgood 2017) argues that efforts to prevent or reduce internal loading are more cost-effective than BMPs in preserving or enhancing water quality of lakes. The ability to predict internal P loading rates would be especially useful under at least two common scenarios. First, in lakes where further development is anticipated (e. g., expanded or intensified agricultural land use, urbanization, etc.) increased external P loading can accelerate the rate of hypolimnetic oxygen depletion (Cornett and Rigler 1980) leading to a longer and more severe anoxic period that would induce new, or increase existing internal loading. Second, the “browning” of lakes as a result of decreased atmospheric S deposition and increased runoff due to global climate change (Monteith et al. 2007, Finstad et al. 2016) leads to stronger and longer thermal stratification (Williamson et al. 2015) and lakes that previously had no or only mild hypolimnetic anoxia may experience internal loading for the first time.

Kopáček et al. (2005) have argued that the presence of naturally occurring aluminum hydroxides may be responsible for some of the variability seen in anoxic P release rates. Aluminum has a high sorption capacity for P in the sedimentary matrix and is not susceptible to redox-mediated dissolution, thereby binding P in the sediments permanently. Lakes with sufficient quantities of aluminum hydroxides in their sediments would display much lower release rates than lakes with less aluminum.   They used a sequential extraction procedure to analyze P, Al, and Fe fractions in a collection of European and North American lake sediments. Measured fractions included bicarbonate/dithionite (BD) that extracts reductant soluble P and Fe, and NaOH that extracts Al and Al-bound P.

Their data showed that 1) in lakes with elevated Al input from acidified soil most of the extractible P was released in the NaOH fraction, whereas in non-acidified lakes most P was released in the BD fraction; 2) that in P-spiked sediments most added P was recovered in the NaOH fraction in Al-rich lakes, but in the BD fraction in Al-poor lakes; and 3) that sediments enriched with Al saw decreases in BD-extractible P and increases in NaOH-extractible P. Kopáček et al. (2005) conclude that in lakes where the sediment molar ratio of Al:P is greater than 25, or Al:Fe is greater than 3, most P will be associated with aluminum hydroxides and will not be susceptible to redox-mediated release. The Al:P hypothesis has been tested by James (2011), and by James and Bischoff (2015) in Half Moon Lake, Wisconsin and in a collection of sediments from Minnesota and Wisconsin lakes subjected to experimental alum addition. Here we test the Al:Fe hypothesis by re-examining the P release rates from the profundal sediments of 57 natural lakes from eastern glaciated North America under standardized conditions (Ostrofsky et al. 1989) and reanalyzing archived subsamples of those same sediments using a sequential extraction technique that allows partitioning of P between iron-bound (BD-extractable) and aluminum-bound (NaOH-extractable) fractions. Further, we examine the variability of Al:Fe ratios with increasing water depth in the sediments to two lakes.

Methods

We used P release rate data as a measure of potential internal loading from a 57-lake data set compiled by Ostrofsky et al. (1989). In summary, surficial profundal sediments were collected from natural lakes from eastern glaciated North America. The data set included 5 lakes from the Algonquin Park/Haliburton region of Ontario, 20 from Connecticut, 18 from Vermont, 8 from Pennsylvania and 6 from New York. These lakes spanned the trophic continuum ranging from 5 to 111 $\mu g \cdot L^{-1}$ spring total phosphorus and from 0.11 to 2.87 $meq \cdot L^{-1}$ alkalinity. They ranged in size from 7 to 556 ha, and drainage basin:lake area ratio from 2.4 to 393. Sediment collected from each lake was partitioned, and a fresh fraction used to determine P release rate under anoxic conditions, and an oven-dried fraction used for chemical analyses.

Chemical analyses – We reanalyzed the archived sediment samples previously described by Ostrofsky (1987) using a slight modification (Hupfer et al. 1995) of an extraction technique described by Psenner et al. (1988). The extraction sequence used 1 M NH_4Cl (interstitial dissolved P and loosely adsorbed P), 0.1 M bicarbonate/dithionite (BD) (redox-sensitive P, largely iron-bound), 1 M NaOH at 25 °C (P bound to oxides of Al and some Fe nnot extracted with BD), 0.5 M HCl (calcite- and apatite-bound P), and finally 1 M NaOH at 85 °C (mostly organic-bound P). This latter technique allowed the separation of iron-bound and aluminum-bound P species that the former technique did not. Iron and aluminum were measured colorimetrically on both the BD and $NaOH_{25\,°C}$ extracts using the colorimetric technique described by Kopáček et al. (2001).

Lake and sediment characteristics and P release rates – Chemical and physical characteristics of the 57 lakes and their sediments have been described previously (Ostrofsky 1987) and P release rates have been reported (Ostrofsky et al. 1989). In brief, sediments were contained in dialysis membranes, incubated in anoxic distilled water, and P concentrations in that incubation water measured daily (see Ostrofsky et al. 1989 for details). Release rates are given as μg P released from 25 cm^3 contained sediment per day (($\mu g\ P \cdot 25\ cm^{-3} \cdot day^{-1}$).

We sought empirical relationships that would predict release rates from lake characteristics and sediment characteristics described above (BD-Fe, NaOH-Al, NH_4Cl-P, BD-P, $NaOH_{25}$-P, HCl-P, and $NaOH_{85}$-P).

Variation in aluminum and iron with lake depth - To measure the variability of Al and Fe in lake sediments we sampled surficial sediments at various locations along several transects across Conneaut Lake and Lake Pleasant, northwestern Pennsylvania. Both lakes are mesotrophic with mid-summer TP around 15 µg/L. We sampled only where water depth exceeded thermocline depth in order to assess those sediments likely to be overlain by anoxic water during summer stratification. Overall, we collected 30 samples from Conneaut Lake ranging in water depth from 6.7 to 18 m, and 34 samples from Lake Pleasant ranging in water depth from 5.8 to 13.4 m. Iron and aluminum were measured on the BD and NaOH extracts, respectively, using the colorimetric method (Kopáček et al. 2001).

Results

Distribution of P species, Fe and Al in lake sediments – Total extractible P (NH_4Cl-P + BD-P + $NaOH_{25}$-P + HCl-P + $NaOH_{85}$-P) ranged from 434 to 3474 ug·g^{-1} sediment dry weight (mean = 1261, SE = 9.17). There was no relationship between total extractible P and lakewater spring TP (r = 0.16). The variability in total extractible P among the lakes , as measured by coefficient of variation, was very much less than the variability in the component P fractions suggesting that lakes across a trophic continuum have sediment P that is more similar quantitatively than qualitatively. Mean contributions from NH_4Cl-P, BD-P, $NaOH_{25}$-P, HCl-P and $NaOH_{85}$-P were 1.3, 30.0, 37.7, 35.5, and 5.6% of total extractable P, respectively, although there was considerable variation among lakes (Table 1). Mean BD-extractable Fe was 13,869 µg Fe·g^{-1} sediment dry wt. and mean NaOH-extractable Al was 4,476 µg Al·g^{-1} sediment dry wt. (Table 1).

Much of the variation in sediment chemistry could be explained by differences in lake characteristics. The ratio of drainage basin area to lake area (A_d/A_o) was strongly correlated with HCl-P, both as mass (µg P·g^{-1} sediment dry wt.) and as percent of total extractable P (r = 0.63 and 0.45, respectively, $p < 0.001$). Lake water alkalinity (meq·L^{-1}) was negatively correlated with NaOH-P, both as mass and as percent of total extractable P (r = -0.50 and -0.62, respectively), negatively with NaOH-Al (r = -0.62) and Al:Fe molar ratio (r = -0.46), and positively with BD-P as a percent of total extractable P (r = 0.59), in all cases, $p < 0.001$. BD-Fe was not correlated with any lake characteristic, but was correlated with other sediment chemical variables. BD-P and BD-Fe were significantly correlated (r = 0.65, $p < 0.001$), but the predictive power of the relationship was compromised by several outliers with anomalously high concentrations of BD-P above BD-Fe concentrations of 20,000 µg·g^{-1} sed dry wt. There were no significant correlations between lake water alkalinity and either BD-P or BD-Fe.

Phosphorus release rates – P release rates (0.06 – 27.12 µg P·25 cm^{-3}·day^{-1}) were negatively correlated with the Al:Fe molar ratio (r = -0.65, $p < 0.001$), negatively with %$NaOH_{25}$-P and %$NaOH_{85}$-P (r = -0.33 and -0.37, respectively, $p < 0.01$) and positively with total extractable P (r = 0.35, $p < 0.01$) and BD-P (r = 0.50, $p < 0.01$). Sediments with a ratio greater than about 3 all had very low release rates suggesting that lakes with similar sediments would not be plagued by high rates of internal P loading (Black, Brewer, Little McCauley, May, Peacham, West Side, and Wolcott). However, many sediments with Al:Fe molar ratios less than 3 also have low rates of P release. Removing the seven sediments with Al:Fe >3 and examining the remainder in isolation we found that P release rates were most strongly positively correlated with BD-P and %BD-P ($r = 0.44$ and 0.59, respectively, $p < 0.001$) and the strongest negative correlation was with %$NaOH_{85}$-P ($r = -0.39$, $p < 0.01$). Although the correlation was weaker between release rate and BD-P than it was with %BD-P, the data were more tightly clustered with the exception of 5 outlying sediments (Caspian, Findley, Harvey's, Shadow, Sugar lakes, Figure 2). These 5 outlying sediments are unique in that they have anomalously high concentrations of BD-P, both in terms of mass and as percent of total extractable P, and anomalously low contribution of $NaOH_{85}$-extractable P (Table 2). Removing these 5 sediments from the data set, remaining release rates showed significant positive correlations with BD-P and %BD-P ($r = 0.69$ and 0.63, respectively, $p < 0.001$), and significant negative relationship with Al:Fe ($r = -0.46$, $p < 0.001$), %$NaOH_{85}$-P and %$NaOH_{25}$-P ($r = -0.29$ and -0.29, respectively, $p < 0.05$) Graphing P release rate of these remaining sediments as a function of BD-P gives the model:

$$\text{Release Rate } (\mu g\ P \cdot 25\ cm^{-3} \cdot day^{-1}) = 0.0256 * \text{BD-P } (\mu g \cdot g^{-1} \text{ sediment dry wt.}) + 0.0327 \quad r^2 = 0.40 \qquad [1]$$

A similar model with % BD-P gives:

$$\text{Release Rate } (\mu g\ P \cdot 25\ cm^{-3} \cdot day^{-1}) = 0.3154 * \%\text{BD-P} - 0.8417, \qquad r^2 = 0.40 \qquad [2]$$

Using combinations of the above 5 factors (BD-P, %BD-P, Al:Fe, $NaOH_{25}$-P, $NaOH_{85}$-P) with the strongest correlation resulted in a step-down multiple regression models with r^2 values between 0.40 and 0.49. The model with the greatest predictive power was:

$$\text{Release Rate } (\mu g\ P \cdot 25\ cm^{-3} \cdot day^{-1}) = 0.027 * \text{BD-P } (\mu g \cdot g^{-1} \text{ sed. dry wt.}) - 0.047\ (\%NaOH_{25}P) + 2.028$$

$$r^2 = 0.49 \qquad [3]$$

Distribution with Depth – In the two lakes we examined we found that both Al and Fe in the surficial sediments individually increased with increasing water depth, however Fe increased more rapidly. The result was that the molar ratio of Al:Fe declined significantly with increasing depth (Figures 3 and 4).

Discussion

Our results support the conclusions of Kopáček et al. (2005) that lakes with sedimentary aluminum to iron molar ratios in excess of ~3, and perhaps as low as 2.5, will have very low rates of internal loading. The relationship between P release rates and Al:Fe in our sediments appears to be hyperbolic, although fitting a hyperbolic regression to the data would not lead to reliable predictions since the change in P-release at low Al:Fe ratios is steep, and slight changes in Al:Fe lead to large changes in release rate. Instead, we examined those sediments with Al:Fe < 3 that also had very low P release rates and asked if these sediments had some attributes markedly different from those with greater release rates. We compared the means of this former group to those of the latter and found no differences with respect to either the concentrations or the percent contribution of the 5 P fractions. There were also no significant differences in comparisons of mean Al, Fe, alkalinity, S, or drainage basin:lake area ratio. So we are left with the hypothesis that in lakes with sedimentary Al:Fe molar ratios greater than ~3 internal loading of P from the sediments will not be significant. In lakes with sediment ratios below 3, release rates are highly variable. These latter sediments were examined in isolation and two groups emerged. In one group, P release rates were significantly correlated with reductant-soluble P (BD-P). This result is consistent with the model proposed by Nürnberg (1988) based on P release from incubated sediment cores from 7 diverse lakes, with the data presented by James (2011) based on 10 sediment samples from Half Moon Lake, and is also consistent with the paradigm that redox-mediated shifts in the solubility of iron is the prevailing mechanism for internal P loading in lakes. In the other group there was no such correlation, and members of this group were characterized by very high BD-P, both as mass and as percent of total extractable P, and with very low concentrations of %$NaOH_{85}$-P. We speculate that a possible reason these sediments have lower P release than their BD-P concentrations would suggest is due to the nature of the organic matter present. While these sediments have significantly lower $NaOH_{85}$-P than the other sediments, they do not differ with respect to total organic matter as measured by loss on ignition (LOI, data in Ostrofsky 1987). These observations suggest that the organic matter is largely allochthonous material, rich in humates, with low P content. This organic matter may provide binding sites to recapture P released from iron oxyhydroxides under anaerobic conditions (de Vicente et al 2008).

Our data present two arguments for caution in predicting P release rates from BD-P concentrations alone. The first is that some lakes may have high concentrations of BD-P yet also have Al:Fe > 3. In our collection of 57 lake sediments, the 7 with Al:Fe > 3 had BD-P concentrations as high as 224 ug $P \cdot g^{-1}$ sediment dry wt. but there were also 24 other sediments with lower concentrations but with higher P release rates. In this case, predicting P release from BD-P alone would result in an overestimate. The second argument is that sediments with P-poor organic matter may not have high release rates in spite of high concentrations of BD-P, again resulting in an overestimate. Consequently, based on our sample of 57 diverse lakes we used a decision tree analysis to model P release rates (Figure 5). Lake sediments with Al:Fe molar ratios > 3 have little or no P release. Lake sediments with Al:Fe less than 3 and with BD-P concentrations above 1000 $\mu g \cdot g^{-1}$ sediment dry wt. and %$NaOH_{85}$-P < 2.5 were very similar having a mean P release rate of 15.4 ± 0.68 $\mu g\ P \cdot 25\ cm^{-3} \cdot day^{-1}$. In lake sediments with Al:Fe less than 3 and with BD-P concentration less than 1000 $\mu g \cdot g^{-1}$ sediment dry wt. and %$NaOH_{85}$-P > 2.5 P release rates were best described by a multivariate model (equation [3]) using BD-P concentration and %$NaOH_{25}$-P as independent predictors.

Our correlation analyses suggest that there is no relationship between lake trophic status measured as TP_{spr} and either total sediment P (Ostrofsky 1987) or total extractable sediment P. However other lake characteristics did influence the distribution of chemical P species present. HCl-P, which is assumed to be P associated with Ca was in greatest concentrations in those lakes with highest alkalinity, measured as $mg \cdot L^{-1}\ CaCO_3$, where biogenic precipitation of Ca-P compounds is common (Dittrich et al. 1997) and in those lakes with largest A_d/A_0 presumably due to greater watershed stream channel length leading to more erosion and delivery of detrital apatite to the lake. Lakes with low alkalinity inhabit watersheds with poorly buffered soils more likely to export mobilized Al. Consequently, these lake have higher concentrations of Al, and Al-bound P, extracted as NaOH-Al and NaOH-P, that in turn affect the Al:Fe ratio. In general then, lakes in poorly buffered basins would be more likely to have low rates of P release from anoxic sediments due to their sediments being richer in Al, with higher Al:Fe ratios.

Our absolute flux rates are not directly transferable to lakes however. The geometric effects of containing sediments within a dialysis membrane with high surface to volume ratio relative to in situ benthic sediments are unknown. Nevertheless, the patterns we observed have some immediate application to lake management. First, our results indicate that the molar ratio of Al:Fe appears to be a function of depth, at least in the two lakes we examined. In both Conneaut Lake and Lake Pleasant we observed a significant decrease in this ratio indicating that shallow hypolimnetic waters would require less alum or poly-aluminum chloride to effectively curtail internal P loading than deeper hypolimnetic regions. Aluminum treatment efforts tailored to depth-specific Al:Fe ratios could potentially result in lower management costs for lake remediation. Second, in lakes with high Al:Fe sediment ratios lake managers could have more confidence that external P load reductions or increases would result in predictable changes in lake trophic status without having to second guess the effects of internal P loading. And finally, in lakes low Al:Fe sediment ratios the relative magnitude of sediment P release could be anticipated given the results of sediment P fractionation.

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Table 1: Characterization of the sediment samples. All P species, Fe and Al reported as $\mu g \cdot g^{-1}$ sediment dry wt.

	NH_4Cl-P	**BD-P**	**$NaOH_{25}$-P**	**HCl-P**	**$NaOH_{85}$-P**	**Total Ext-P**	**BD-Fe**	**NaOH-Al**
Low	0.8	43.1	71.0	22.5	34.5	434	1702.4	1663.2
High	59.5	2182.4	1692.2	1120.4	139.3	3474	59436	7845.9
Mean	12.6	410.6	477.2	299.6	61.9	1261	13869.2	4476.1
Std Error	1.4	53.7	41.5	30.1	2.8	9.2	1423.9	217.4

Table 2: Five outlying sediments on Figure 2 (from Caspian, Findley, Harvey's, Shadow and Sugar lakes) have significantly higher mean concentrations (± s. e.) of BD-P (t-test, $p < 0.001$), % BD-P ($p < 0.001$) and significantly lower contribution from $NaOH_{85}$-P ($p < 0.005$) than the remaining 59 sediments. BD-P in µg $P \cdot g^{-1}$ sediment dry wt.

Sediment	**BD-P**	**%BD-P**	**%$NaOH_{85}$-P**
5 Outlying Sediments	1681 ± 203	63 ± 2	2 ± 0.2
Remaining 59 Sediments	303 ± 24	27 ±2	6 ± 0.3

Figure Legends

Fig 1 The relationship between the molar ratio of NaOH-extractable Al and BD-extractable Fe and phosphorus release rate for 57 lake sediments

Fig 2 The relationship between buffered dithionite-extractable-P and phosphorus release rate from sediments of 50 lakes with Al:Fe < 3.0. The 5 outlying sediments all have anomalously high concentrations of BD-P (>1000 $\mu g \cdot g^{-1}$) and low contributions from $NaOH_{85}$-P (< 3% total extractable P). The remaining 45 sediments are correlated with BD-P (r = 0.69)

Fig 3 Molar ratio of Al:Fe as a function of water depth in Lake Pleasant based on 34 sediment samples

Fig 4 Molar ratio of Al:Fe as a function of water depth in Conneaut Lake based on 30 sediment samples

Fig 5 Decision tree that best explains the rate of phosphorus release rates from the 57 lake sediments analyzed

Appendix Legend

Raw data from analyses of lake sediments. All concentrations (P species, Al, and Fe) in $\mu g \cdot g^{-1}$ sediment dry wt.), TP_{spr} in $\mu g \cdot L^{-1}$, and P release rate in $\mu g\ P \cdot 25\ cm^{-3} \cdot day^{-1}$.

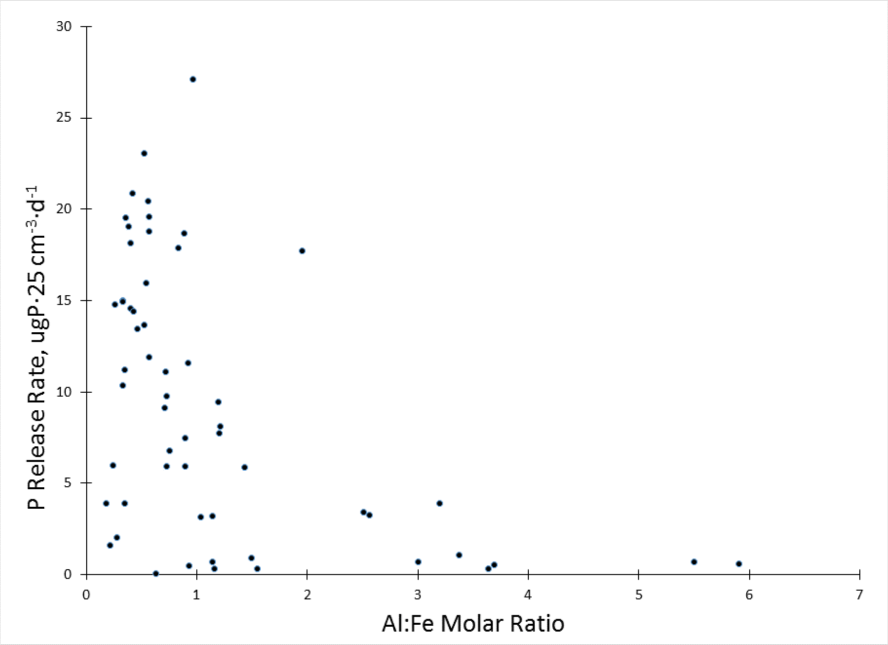
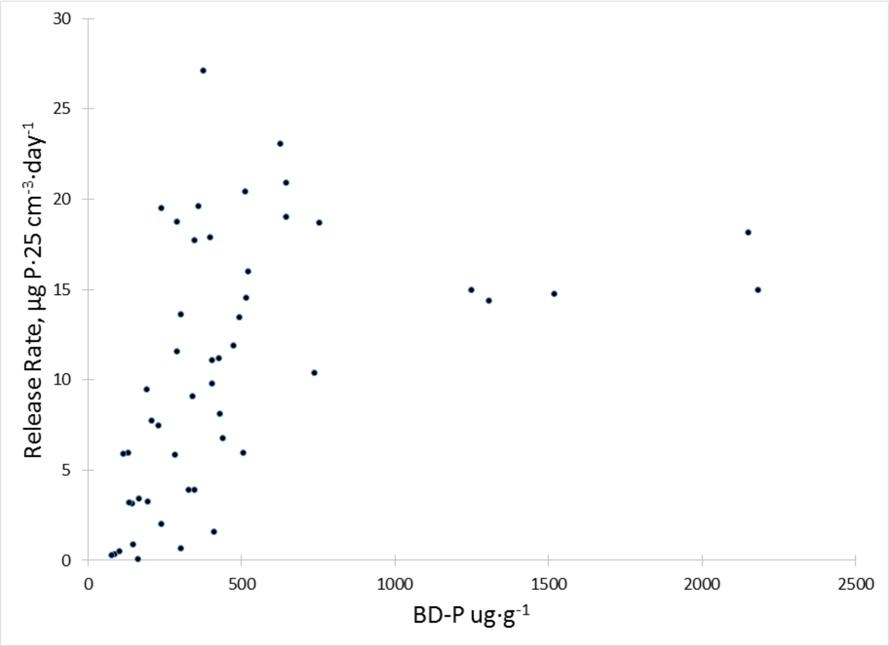
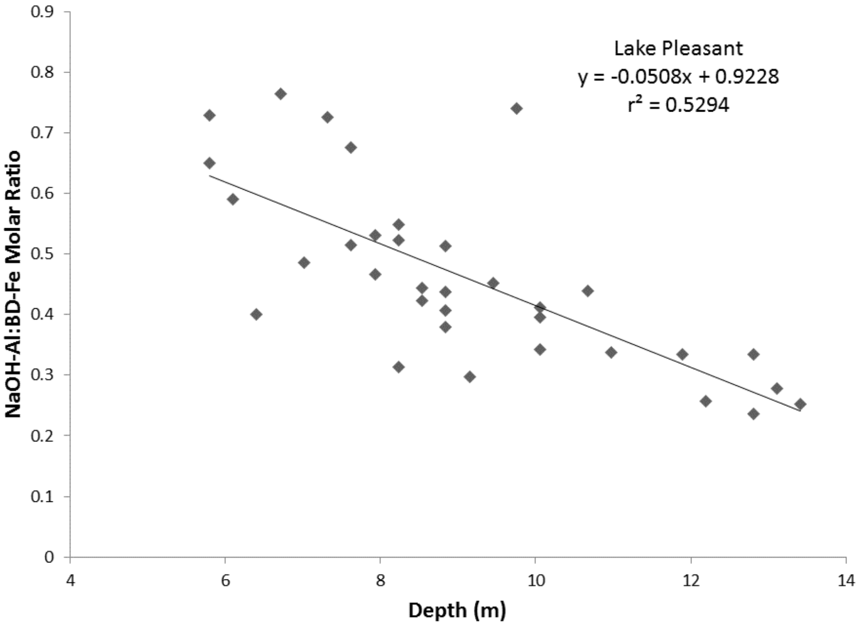

P Release Rate, ugP·25 cm⁻³·d⁻¹
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
Al:Fe Molar Ratio

Fig 1

Fig 2


30
25
20
15
10
5
0
Release Rate, µg P·25 cm^{-3}·day^{-1}
0
500
1000
1500
2000
2500
BD-P ug·g^{-1}

344 Fig 3


Lake Pleasant
y = -0.0508x + 0.9228
r² = 0.5294
NaOH-Al:BD-Fe Molar Ratio
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
6
8
10
12
14
Depth (m)

345

Fig 4

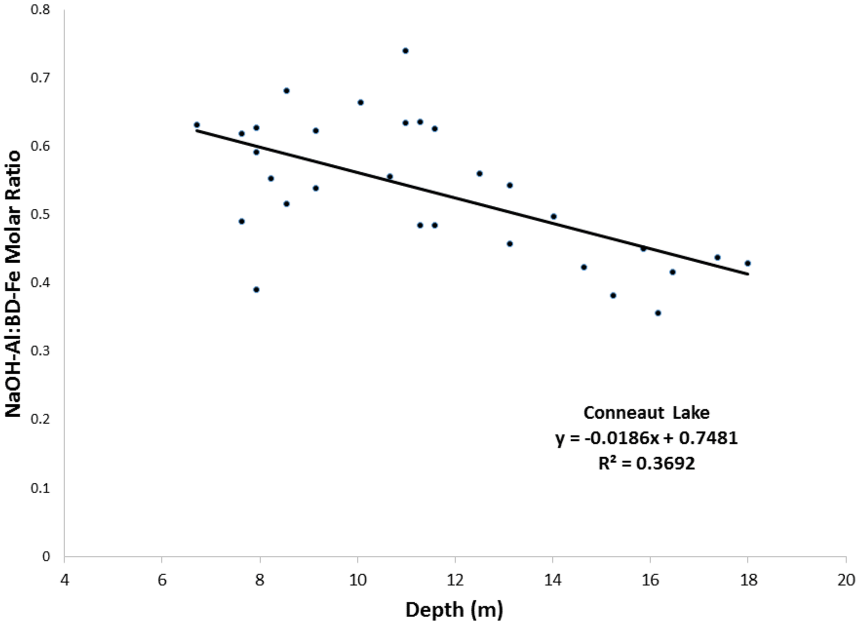
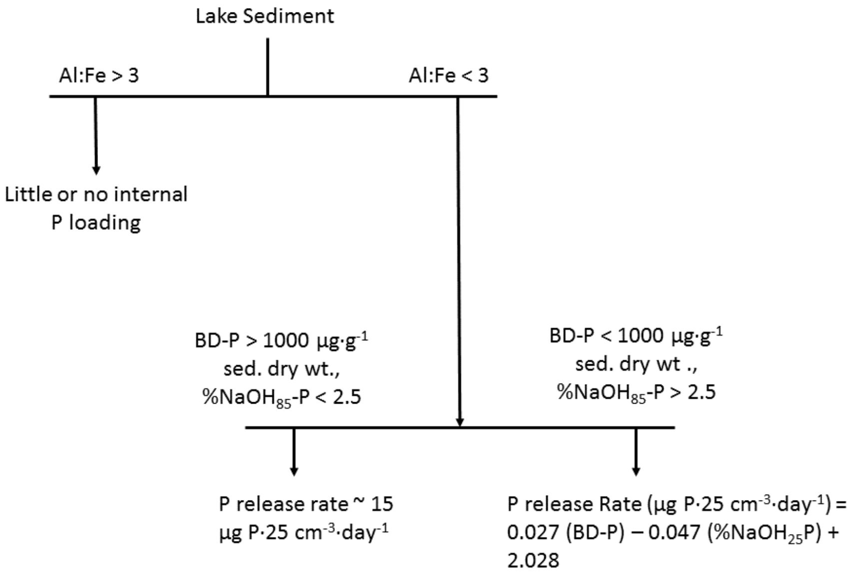

NaOH-Al:BD-Fe Molar Ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Depth (m)
4
6
8
10
12
14
16
18
20
Conneaut Lake
y = -0.0186x + 0.7481
R² = 0.3692

Fig 5


Lake Sediment
Al:Fe > 3
Al:Fe < 3
Little or no internal P loading
BD-P > 1000 µg·g^{-1} sed. dry wt., %NaOH$_{85}$-P < 2.5
BD-P < 1000 µg·g^{-1} sed. dry wt ., %NaOH$_{85}$-P > 2.5
P release rate ~ 15 µg P·25 cm^{-3}·day^{-1}
P release Rate (µg P·25 cm^{-3}·day^{-1}) = 0.027 (BD-P) – 0.047 (%NaOH$_{25}$P) + 2.028

Appendix

Lake	NH4Cl-P	BD-P	NaOH-P (25)	HCl-P	NaOH-P (85)	NaOH-Al	BD-Fe	meq
Kearney	8	117.3	616.8	633.7	66.2	5832.5	13203	0.1
Costello	1.3	75.9	656.5	359.1	41.7	6734	7964.4	0.1
Brewer	22.2	86.7	884.8	243.6	55.1	7845.9	2750.5	0.1
Clarke	4.1	392.6	928.6	356.8	44.8	6225.9	59436	0.1
Little McCauley	11.7	43.1	683.3	118.3	41.1	7552.9	2842	0.1
Found	17.4	162.6	591.1	124.7	47.4	4798.4	15798.1	0.1
Mt. Tom	18.7	347.6	727.9	157	70.3	6509.7	6891.2	0.4
West Hill	18.8	166.4	761.8	127.8	81.8	5995.9	4937.4	0.1
Highland	18.1	196.1	1223.8	130.7	139.3	7781.4	6289.1	0.3
Dunmore	2.5	411.3	505.8	413	88.4	3600.4	34340.8	0.3
May	9.3	160.9	361.1	179.2	44.9	5913.7	4080.6	0.3
Groton	8.7	44.8	613.7	212.7	58	7736.6	3480.5	0.2
Quassipaug	13.9	402.7	1692.2	108	76.7	6971.6	19734.3	0.1
Wolcott	9.4	87.4	608.6	122.7	48.3	5128.8	2916	0.2
Island	8.9	103.5	718.8	198.8	67.7	6716.5	14977	0.2
Peacham	23.3	180.3	391.6	197.4	54.2	5646.9	3167.3	0.3
Beech	7.4	123.1	218.5	1101.4	35	2786.4	7322.9	0.3
Green	4.3	132.1	274.4	1050.7	44.1	3625.6	10299.7	0.3
Pine	3	115.4	224.1	1120.4	39.9	3348.6	7726.2	0.3
Cranberry	9.9	125.7	181.8	776.9	39.8	3604.1	3335.8	0.3
Quonnipaug	2.6	425.5	590.7	102.6	75.2	5154.5	30962.8	0.6
Taunton	5.6	189.9	624.7	298	72.6	6001.6	10425.8	0.5
Squantz	3.5	738.8	1315.3	157.5	84.8	6464.9	40388	0.5
Bantam	16.8	430.8	609	266.8	97.6	5475.2	9335	0.7
Waramaug	6.1	515.4	1270.9	241.8	66.7	6018.9	31230.7	0.5
West Side	21.9	223.6	646.9	188.4	81.4	5290.3	3420.1	0.9
Tyler	7	146	254.4	188.6	63.2	3272.1	4521.8	0.8
Cream Hill	7.6	142.9	278.6	121.1	74.9	2792.1	5585	0.5
Iroquois	8.7	404.8	258.8	414	54.3	3499	10032	0.9
Carmi	10.7	290.3	109.6	704.5	55.3	2307	5190.9	0.7
Fairfield	7.9	341.4	116.9	696.3	35.8	2931.7	8563.7	0.6
Eden	4.2	85.4	501.1	257.9	57	6765.9	12074.3	0.5
Shadow	11.6	2182.4	880.3	343.5	56.3	4820.2	29940.9	0.9
Crystal (Vt)	4.3	77.7	451.7	295.5	91.3	6765.2	9020.4	0.7
Echo	8.9	397.9	452.6	362.5	77.4	5600.8	13881.7	0.7

Morey	8.8	374.3	107.7	331.6	34.5	2623.2	5629.9	0.9
Fairlee	11.7	282.3	450.8	313.8	58.6	5847.9	8450	0.6
Canadohta	7	521.2	426.9	71.1	56.9	3740.7	14188.7	0.8
Black	19.2	93.9	145.3	116.3	59	2778.2	1702.4	1.0
Ball	8.8	751.9	724.4	237.2	99.7	5187.4	12143.3	1.1
Caspian	19.4	1306	522.6	491.1	53.7	4467.8	21609.4	1.3
Parker	7.7	637.5	323.1	517.2	64.2	4076.9	20074.2	1.3
Harvey's	27.3	2150.3	673.4	416.3	64.9	4457.7	23173.7	1.3
Conneaut	6.6	646.8	225.6	116	53.5	2912.8	15746.6	1.4
Crystal (Pa)	8.9	301.9	158	40.3	65.6	1693.4	6691.4	1.2
Sandy	2.4	238.5	480.6	22.5	103.6	6025.8	44831.8	1.2
Sugar	9.8	1249	431.3	141.8	49.4	3085.2	19289	1.3
Bear	8.4	290.1	290.4	209.3	67.9	2632.2	9566.5	1.0
Edinboro	5.7	493.6	517.8	84.4	86.1	3850.6	17385.6	1.6
Pleasant	10	627.9	165.2	96	37.3	2973.7	11676.8	1.6
Findley	14	1519.6	528.9	176.5	48.2	2914.8	23104.2	1.6
Lower Cassadaga	57.3	208.5	71	285.7	38.8	2132.8	3669.4	1.7
Silver	43.1	359.8	112	531.2	45.1	1663.2	6042.3	1.7
Java	17.5	512.5	570.5	127.1	86.1	3258.4	12101.8	1.7
Linsley	0.8	238.4	731.7	114.5	71.2	5231.9	30497.6	1.9
Kenosia	2.2	474.4	373.6	268.7	52.6	5288.1	19099.2	1.6
Lime	59.5	228.9	53.5	165.5	34.8	1806.7	4161.2	2.3
East Twin	20.7	134.5	69.7	374.2	64.1	2469	4475.6	2.3
LeBoeuf	16.9	645.8	364.4	86.8	76.9	3261.9	16045.9	2.2
Shelburne	14.6	301.5	151.1	247.6	42.9	2997.1	5417.8	2.1
Ewell	14.5	437.8	173.7	289.4	57.7	3695.6	10125.4	2.1
Wononscopomuc	7.6	347.7	166.9	321.9	52.2	3394.8	20190.5	2.5
Mudge	20.7	505.3	137.3	266.3	46.8	2360.9	19869.7	2.8
Wononpakook	8	328.2	163.8	344	58.1	2129.2	24604	2.6