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Primary Research Paper

Reconstructing the historical trophic status of northwestern Pennsylvania lakes using GIS

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Abstract

From each of 46 watersheds in glaciated northwestern Pennsylvania we estimated phosphorus export (kg P/ha/yr) from weekly or twice-weekly measured stream phosphorus concentrations and measured stream discharges, and determined land covers using GIS. Simple and step-down multiple regression analyses yielded models that explained 24% of the variation in P export using land cover within whole watersheds, and 64% of the variation using land cover within 200 m riparian buffers. We used these models to predict P loading to seven lakes and found that predicted lake [P] was consistent with measured lake [P]. To estimate pre-settlement lake [P] we reapplied the P export models with the assumption that human-impacted land covers were originally forests. Predicted (hindcast) pre-settlement lake [P] indicated that six of the seven lakes were edaphically mesotrophic ($10 < [P] < 20$ μg/l). Lake remediation targets set on the assumption that area lakes were historically oligotrophic ($[P] < 10$ μg/l) will be unattainable.

Introduction

Historical water quality records that allow the trophic assessment of lakes prior to and during early human settlement of their catchment areas rarely exist. Consequently, limnologists and lake managers are unable to directly determine the natural trophic states or rates of eutrophication of affected lakes. The ability to reconstruct past trophic state is of particular interest at present. Section 303(d) of the U.S. Clean Water Act of 1972 (CWA) requires that each state develop a list of the impaired waters that do not meet designated water quality standards. For each of these impaired waters, the offending contaminant (nutrients, suspended solids, mercury, heat, etc.) is identified, and the total maximum daily load (TMDL) of that contaminant consistent with water quality standards is calculated. This TMDL serves as a goal for environmental remediation by federal, state, and local agencies, or by private NGOs. While most of the impaired water bodies on the 303(d) list are streams, many lakes are also listed. For example, the U.S. EPA (2002) lists 71 lakes, reservoirs, and ponds in Pennsylvania, and Mattson & Isaac (1999) indicate that 561 lakes in Massachusetts are designated impaired.

Although water bodies are affected by a variety of pollutants, the overwhelming majority of the lakes in the two examples cited above are listed for nutrient related problems (macrophytes, algae, low dissolved oxygen, etc.). Phosphorus (P) is invariably the most important nutrient since it most often determines lake trophic status. Higher P concentrations in lakes lead to increased standing crops of algae and submersed vascular plants, decreased water clarity, periods of anoxia in the hypolimnion and a shift in community structure toward more tolerant, and often less desirable, species of fish. The importance of P loading in determining the degree of eutrophication is widely accepted and consequently, many TMDLs have focused on reductions in P loadings to lakes. The CWA specifies that TMDLs set specific targets for remediation of impaired water bodies and state agencies have adopted a variety of strategies for determining these targets, and have assumed that lake and watershed management efforts will be able to reach them. However, in the absence of historical data on P concentrations in any particular lake, designated targets may be unattainable. For example, the Pennsylvania Department of Environmental Protection (2001) recently filed a TMDL that specified a 10% reduction in Carlson's (1977) trophic state index (TSI) for Conneaut Lake, Crawford County, PA. The TSI is based on a logarithmic scale, and a 10% reduction in TSI requires a 30% reduction in P concentration. Conneaut Lake currently has a springtime P concentration of ~19 μg/l. It is quite possible that in its pre-settlement state the P concentration of the lake was not 30% lower than its current level. If so, this remediation target is unattainable and the expenditure of public funds without the possibility of success erodes public confidence in state agencies and diverts scarce funds from other projects with more attainable goals. There is a pressing need to determine historic (pre-settlement) P concentration where such data do not exist as a guide to the setting the highest water quality (lowest trophic state) attainable using current lake restoration strategies.

There are several approaches to estimating historical P concentration in lakes. One approach might be to use nearby lakes in similar geochemical settings that are unaffected by human activities. However, in many regions, no lake has escaped some level of human impact. A second approach might be to analyze a lake sediment core for diatoms and reconstruct historical P concentrations using known diatom phosphorus preferences (e.g., Reavie et al., 1995, Brenner et al., 1996). Use of diatom-inferred phosphorus concentrations has become a popular method for paleolimnological reconstructions of lake trophic state. However, one of the basic assumptions of constructing paleoecological transfer functions is that historical conditions fall within the range of modern calibration sets (Sachs et al., 1977). In many regions, no lakes have escaped some degree of impairment and this assumption cannot be met. Further, this method is expensive, time-consuming, and requires considerable taxonomic expertise.

A third approach makes use of watershed P export models. These models are based on empirically derived export rates for various land covers. A compilation of rates presented by Reckhow et al. (1980) has found wide use among state and federal agencies and lake managers in estimating P loads to lakes. In general, forests export far less P than does land in agricultural use and it can be reasonably assumed that prior to settlement, lake drainage basins in eastern North America were overwhelmingly forested. An estimation of pre-settlement P concentration could be obtained by using this approach, and would be most accurate if regionally-specific export rates were used rather than the averages suggested by Reckhow et al. (1980). In comparisons of historical reconstructions on the trophic status of lakes, Reavie et al. (2002) and Bennion et al. (2005) demonstrated that watershed models provided more accurate predictions than did diatom-inferred models.

Our objective is to extend the watershed model approach by developing a regionally specific P export model based on GIS-determined land cover for the glaciated region of northwestern Pennsylvania, to test the model by comparing current measured P concentrations to predicted P concentrations for natural lakes in the region, and finally to remove the influence of human-impacted land covers and estimate historical P concentrations. We hypothesized that prior to human impact lakes in this area were edaphically mesotrophic as a result of watersheds characterized by relatively nutrient-rich sedimentary rock overlain by calcareous glacial drift, and that this natural mesotrophic state represents the best attainable target for lake remediation efforts.

Methods

Description of study area

Natural lakes in northwestern Pennsylvania are limited to a relatively small glaciated region (approx. 9200 km^2) that includes all of Erie, Crawford, and Mercer, and small portions of adjacent counties. Within this region there exist only eight kettle lakes between 300 and 400 m asl (Fig. 1). The lakes range in size from 6 to 378 ha. The bedrock geology is Devonian- and Mississippian-age shale, sandstone, and siltstone of marine sedimentary origin overlain with calcareous glacial deposits. Dominant land cover is mixed forest and agriculture. As a consequence, the lakes have moderately hard water, are mesotrophic to eutrophic, and have periodic deep-water anoxia during the summer months. All are headwater lakes, and most are heavily used for recreation. Brief descriptions of the relevant lake characteristics are listed in Table 1. Crystal Lake was not included in the analysis because it is a small basin imbedded in a large wetland complex lacking inlet streams. Further, the hydraulic regime of this lake and wetland complex is manipulated seasonally by the Pennsylvania Game Commission for waterfowl production. The small number of lakes and the lack of a broad trophic gradient preclude the development of a regionally-specific calibration set based on modern diatom assemblages that is necessary for reliable diatom-inferred phosphorus reconstructions (Sachs et al., 1977; Reavie et al., 2002).

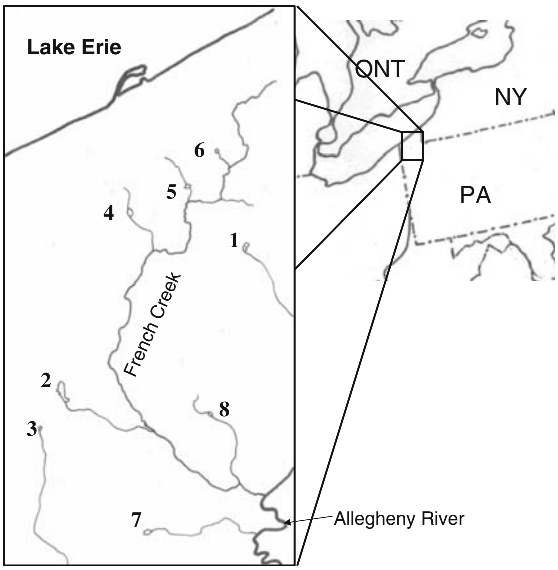

Figure 1. Study area showing the location of lakes and major streams. 1 – Canadohta Lake, 2 – Conneaut Lake, 3 – Crystal Lake, 4 – Edinboro Lake, 5 – Lake LeBoeuf, 6 – Lake Pleasant, 7 – Sandy Lake, 8 – Sugar Lake.

Phosphorus export model

Included sub-catchment basins of Canadohta, Conneaut, Edinboro, LeBoeuf, Pleasant, Sandy, and Sugar lake watersheds were digitized from 1:24,000 U.S.G.S. topographic quadrangles using ArcGIS 9 software (Environmental Systems Research Institute, 2004) and a SummaGridV digitizing tablet. Streams draining these sub-basins were also digitized if delineated on the U.S.G.S. maps, and for each of these streams 50, 100, and 200 m riparian buffers were created. Land cover classifications for each whole sub-basin, and for each of the three buffers within each sub-basin were extracted from the U.S.G.S. National Land Cover Data set (2000).

Phosphorus export (kg/ha/yr) was calculated by collecting water samples for phosphorus analysis at weekly or twice-weekly intervals for at least 12 months from 46 low-order area streams. Total phosphorus concentrations were determined using the phosphomolybdate technique on persulfate oxidized samples (Strickland & Parsons, 1968). Stream discharges were either measured directly with a Marsh–McBirney current meter, estimated from calibrated continuous stage-height recorders, or estimated using area-specific discharge coefficients from adjacent monitored streams. We found no consistent correlations between discharge and phosphorus concentrations, so we estimated phosphorus export as the sum of the products of measured or interpolated phosphorus concentrations and daily discharge estimates divided by watershed area.

We constructed simple and step-down multiple regression models of phosphorus export as a function of land cover (Zar, 1974) for whole sub-basins (n = 46) and for each of the three buffer zones (n = 33). Regressions were run using the decimal percent (i.e., 1.00 = 100%) of all the identified land cover categories, and, with combinations of similar categories. The final choice among the eight models (whole watershed and three riparian buffers, each with individual and with pooled land cover categories) was made on the basis of the amount of variability in P export rates that could be explained.

Table 1. Physical and chemical characteristics of northwestern Pennsylvania lakes

Lake	Location	Area (ha)	Drainage basin area (km^2)	Max. depth (m)	Total [P] (μg/l)	Total alkalinity (mg/l)
Canadohta	41° 48.91′ N 79° 50.28′ W	68	20.3	13.6	27	39
Conneaut	41° 37.5′ N 80° 18.3′ W	378	72.3	19.8	19	73
Crystal	41° 33.21′ N 80° 22.14′ W	6.1	0.28	7.1	23	62
Edinboro	41° 52.78′ N 80° 08.22′ W	167	65.7	9.1	30	67
LeBoeuf	41° 55.61′ N 79° 58.96′ W	32.2	158.6	9.1	48	74
Pleasant	42° 00.22′ N 79° 53.85′ W	23.7	3.6	13.7	36	96
Sandy	41° 20.71′ N 80° 06.43′ W	88.5	7.2	11.4	14	67
Sugar	41° 33.94′ N 79° 56.75′ W	31	56.4	5.5	41	37

Applying the P export model, now ... and then

To assess the utility of the resulting model we used it to estimate the P loading from all watersheds of each of the seven lakes based on current land cover designations. We calculated the total external P load to each lake as the sum of the annual export estimates from each of the component sub-basins. Internal P loads were estimated from the product of measured sediment release rates (Ostrofsky, unpublished data), hypolimnetic sediment areas determined from bathymetric maps, and the duration of the anoxic period. For Edinboro Lake only, an additional loading of 307 kg/yr was included as an estimate of the effects of the Washington Township sewage treatment plant effluent, the only identified point source of P to any of the lakes. To predict the lake phosphorus concentration from annual loading, we used equations derived by Nurnberg (1998, Table 3, Eq. 4) and Ostrofsky (1978, Table 2, Eq. 7), long-term average discharge (Krug et al., 1990) and lake morphometric characteristics. These latter models are insensitive to trophic status so their application should introduce no bias into the projections. Predicted phosphorus concentrations were compared to measured phosphorus concentrations to assess the utility of the model.

To estimate historical P concentrations, current land covers were reclassified to their ‘most likely’ use about 250 years ago. We were guided by the oft-paraphrased comment that in pre-settlement North America a squirrel could travel from the Atlantic coast to the Mississippi River, or from the Gulf coast to James Bay without ever descending to the ground (cf. Adams, 1931; Hamel & Bruckner, 1998), and for northwestern Pennsylvania specifically, that forests made up to 95–100% of the land cover (Whitney & DeCant 2003). Land currently in agricultural, industrial or residential use was most likely forested. Current wetlands probably have not been modified since these areas do not favor either agricultural or residential development. The phosphorus export model was then applied to the revised land covers, and historical phosphorus loading to each lake was calculated. Again, lake phosphorus concentrations were estimated from revised loading rates using the previously described models, discharges, and morphometries. We did not include an internal P load component, assuming that it was historically negligible.

Results

Land cover

The 46 watersheds used to develop the phosphorus export model ranged in size from 4.3 to 3406.4 ha, and measured P export ranged from 0.077 to 0.982 kg/ha/yr. Within these sub-basins U.S.G.S. National Land Cover Data identified 13 different land covers based on 30-m resolution. Sub-basin land covers ranged from 1.2 to 91.3% deciduous forest, 0.0–82.1% pasture/hay, 0.0–37.6% row crops, 0.0–18.6% mixed forest, 0.0–32.3% evergreen forest, 0.0–26.9% low-intensity residential, 0.0–51.5% urban and recreational grasses, 0.0–15.1% commercial/industrial/transportation, 0.0–12.3% woody wetlands, 0.0–8.5% open water, 0.0–1.9% emergent herbaceous wetlands, 0.0–2.0% high-intensity residential, and 0.0–0.4% transitional. The open water classification does *not* include any lake surface, but rather those open areas within wetlands. The transitional land use category is defined by U.S.G.S. as areas with less than 25% vegetative cover that is dynamically changing from one land cover to another. We interpret this category to include heavily timbered areas, old agricultural areas undergoing succession, etc. Table 2 identifies the mean values of each of these land covers in whole sub-basins and in each of the buffers. Riparian buffers tended to have more forest cover, and less agricultural cover than whole sub-basins. The values of the more frequently occurring land cover categories were approximately normally distributed. Those that occurred less frequently were not normal because of the abundance of zeros in the data matrix. The arcsine transformation customarily used to normalize percent or proportion data (Zar, 1974) was not used since categories with large numbers of zeros remained non-normal. To minimize this effect, we pooled some categories assumed to have similar effects on P export to minimize zeros in the data matrix. We combined deciduous, evergreen and mixed forests into total forest; open water, woody wetlands and emergent herbaceous wetlands into total wetlands; pasture/hay, urban/recreational grasses, and transitional into total grasses; and high intensity residential and commercial/industrial/transportation into high-human impact.

Simple regression analyses between single and grouped land cover categories and measured P export revealed few significant relationships. For whole sub-basins, transitional land cover was positively related to P export

$$\text{P export (kg/ha/yr)} = 0.222 + 298.793\ (\%\ \text{transitional}). \quad r^2 = 0.24,\ p = 0.0013 \qquad (1)$$

Within the 50 and 100 m buffers, there were no significant relationships. Within the 200 m buffer there were significant positive relationships with pasture/hay and total grasses, and significant negative relationships with deciduous forest, and with total forest.

We generated eight step-down multiple regression models (whole sub-basin, and 50, 100 and 200 m buffers, each using grouped and ungrouped land cover categories). There were no significant

Table 2. Mean land cover (% of area) as designated by U.S.G.S. National Land Cover Data set for the 46 monitored sub-basins and 33 buffered riparian areas

Land use	Whole sub-basin	50 m riparian buffer	100 m riparian buffer	200 m riparian buffer
Deciduous forest	43.8	51.5	47.0	47.5
Evergreen forest	4.6	8.4	7.6	6.3
Mixed forest	6.0	8.7	7.5	6.8
Open water	0.6	3.7	3.3	2.7
Woody wetlands	0.7	2.7	2.5	2.1
Emergent herbaceous wetlands	< 0.1	0.3	0.3	0.3
Row crop	7.3	3.1	5.2	4.7
Pasture/hay	31.0	19.2	23.6	27.2
Low intensity residential	3.0	1.8	1.8	1.6
High intensity residential	< 0.1	< 0.1	< 0.1	< 0.1
Commerc./Indust./Transp.	1.4	0.3	0.3	0.3
Urban/recreational grasses	1.5	0.3	0.3	0.3
Transitional	< 0.1	< 0.1	< 0.1	< 0.1

relationships between P export and either the grouped or ungrouped land cover categories for the 50 and 100 m buffers, or for the grouped whole sub-basins. The ungrouped sub-basins yielded a significant regression, but only one of the four independent variables was significant at $p = 0.05$. This outcome results in unstable regressions. The 200 m buffer data gave significant regressions with both ungrouped and grouped land covers. With the grouped data, however, few of the independent variables were significant even though the regressions were highly significant ($0.0014 < p < 0.0001$ for step down models using from 2 to 8 independent variables). Ungrouped data gave a significant regression ($p = 0.0010$) using eight independent variables (row crop, evergreen forest, pasture/hay, deciduous forest, open water, mixed forest, urban/recreational grasses, and woody wetlands) where only one of the variables was not significant (row crop, $p = 0.06$), however we felt that the difference between the *p*-value of 0.06 and the *a priori* α of 0.05 was probably of little biological significance. The regression coefficients of the three forest types were similar (from 5.585 to 5.980) so we grouped the forest types and generated a hybrid model

$$\begin{aligned}
\text{P export (kg/ha/yr)} &= -5.808 \\
&\quad + 4.596\,(\%\,\text{row crop}) \\
&\quad + 7.374\,(\%\,\text{pasture/hay}) \\
&\quad + 7.329\,(\%\,\text{open water}) \\
&\quad + 11.176\,(\%\,\text{urban/recreational grasses}) \\
&\quad + 6.787\,(\%\,\text{woody wetlands}) \\
&\quad + 5.841\,(\%\,\text{total forest}). \\
r^2 = 0.634,\quad p = 0.0001 & \qquad (2)
\end{aligned}$$

In our data set there were 13 small (median area 14 ha) monitored sub-basins drained by permanent streams that had no stream channel indicated on U.S.G.S. maps. Since riparian buffers could not be constructed for these sub-basins, we applied the ungrouped sub-basin model (1) to these whole sub-basins. Errors caused by this approach should be small since the total area in question is a small fraction of the lakes' total watershed area.

Predicted vs. measured [P]

Using the P export models ((1) and (2)) we calculated predicted loadings to seven northwest Pennsylvania lakes based on current land covers. Predicted P loads ranged from 315.7 to 7329.2 kg P/yr with predicted [P] ranging from 26 to 65 μg P/l (Table 3). In five of the lakes there was very good agreement between predicted and observed [P]. In LeBoeuf and Sandy lakes predicted [P] overestimated measured [P] by 35 and 77%, respectively.

Hindcasts

When we converted human-influenced land covers to forest, a reapplication of the derived P export models resulted in considerably lower P loads to all lakes. The estimated [P] based on these historically estimated P loads ranged from 6 to 20 μg P/l (Table 3). Current measured [P] range from 1.5 to 2.8 times higher than these historical predictions.

Discussion

Limnologists have long recognized that streams are affected by their watersheds (Hynes, 1975) and that varying land uses within those watersheds have strong effects on various measures of water quality and nutrient export (Allan, 2004). Approaches to modeling these effects have ranged from comparisons of mean export rates among watersheds with different land cover classifications (e.g., Dillon & Kirchner, 1975) to more elaborate multivariate regression models (Mattson & Isaac, 1999; Daly et al., 2002). Further, the widespread

Table 3. Observed, predicted and hindcast total phosphorus concentrations ([TP]) in μg/l for northwestern Pennsylvania lakes based on current and estimated historical land cover. Observed [TP_{spr}] was measured during spring isothermal period

Lake	Observed [TP_{spr}]	Predicted [TP]	Hindcast [TP]
Canadohta	27	26	11
Conneaut	19	30	13
Edinboro	30	31	16
LeBoeuf	48	65	20
Pleasant	36	30	13
Sandy	14	26	6
Sugar	41	42	17

appreciation of vegetated riparian buffers as a best management practice (BMP) to reduce nutrient export to streams acknowledges that the effects of land cover decrease with increasing distance from the stream channel. The data presented above are consistent with this hypothesis in that phosphorus export from 33 watersheds was more closely related to land cover classifications within 200 m of the stream channel than it was with whole watershed classifications. The absence of significant relationships with narrower riparian buffers, however, argues that land cover exerts considerable influence beyond 100 m. The width of this influential buffer can be described by a distance–decay function where nutrient export from more distant areas is gradually reduced through uptake and attenuation during downslope movement (Johnes & Heathwaite, 1997). Distance–decay rates are probably affected by the slope of the valley and the depth and permeability of the soils (Hynes, 1975). Buffers may be considerably wider in steeper slopes than in flatter areas, and on shallow or impermeable soils.

From the 13 land covers identified by the U.S.G.S. National Land Cover Data set in this study, eight (row crops, pasture/hay, open water, urban/recreational grasses, woody wetlands and total forest [= deciduous forest + mixed forest + evergreen forest]) made significant contributions to the P export model.

The contribution of each land cover to phosphorus export from watersheds should be proportional to the magnitude of the regression coefficient. For the most part, this hypothesis was supported with forests contributing less to P export than most other land covers. The model predicts that watersheds with 100% forest cover would export 0.033 kg P/ha/yr. This result is within the range of export values (0.019–0.830 kg P/ha/yr) reported in the compilation of Reckhow et al. (1980). The model predicts that watersheds with 100% pasture/hay would export 1.56 kg P/ha/yr. Again, this result is remarkably close to the average (1.50 kg P/ha/yr) of export rates from grazing and pasture land cover reported by Reckhow et al. (1980). The greatest contributor was urban/recreational grasses which are often intensively managed with heavy and frequent application of fertilizer. The contribution of row crops was anomalously small. This small contribution and the marginal significance in the multivariate model might be the result of a number of factors. Row crops in our watersheds were largely corn, soybeans, and small grains, each of which is managed differently with varying amounts of applied fertilizer (either commercial or organic manures) with varying tillage practices (either conventional or no-till) on fields that may or may not have artificial drainage. All of these variations affect P export (Heathwaite et al., 2000) and the permutations of these and other factors likely results in much higher variability than is found in any of the other land cover classifications. Further, high P export is the result of the coincidence of high soil P saturation, and high hydraulic connectivity (Heathwaite et al., 2000) and the presence of vegetated buffer strips along stream channels and other BMPs may ameliorate the anticipated effects of row cropping. Elimination of row crop land cover from the step down regression model, however, seriously weakened the predictive power of land cover on P export. Daly et al. (2002) report a similar result with their land cover 'semipeat'. Semipeat was associated with gley soil with poor P retention capacity, and with areas of high runoff – suggesting that the P contribution from semipeat land cover should be significant. However, their regression model indicated that these areas were net sinks, rather than sources, of exported P. Similarly, Mattson & Isaac (1999) found that their input variable 'house septics' also had a negative effect (net sink) on loading.

In spite of our row crop anomaly, the multiple regression model predicted P loadings to our seven lakes that allowed the estimation of lake phosphorus concentration with reasonable accuracy. In no case did predicted lake [P] differ from measured P by more than a factor of 1.8. This predictive ability compares favorably to other models based on land cover (e.g., Daly et al., 2002) and on diatoms (e.g., Little et al., 2000; Reavie et al., 2002). The difference between predicted and measured P concentration is the result of the cumulative errors of estimating P export, internal P loading, P retention model, and year-to-year variations in precipitation and runoff as they affect export and lake discharge. Knowlton et al. (1984) showed that median annual variance in lake [P] was 22% of mean [P] in 188 midwestern lakes due to variations in runoff.

Part of the difference may also be explained by overlooked land covers. Within the relatively small watershed of Lake Pleasant, for example, there are areas of gravel mining – a land cover not recognized by the U.S.G.S. land cover data analysis.

The predicted historical [P] for six of the seven lakes in northwestern Pennsylvania fall within the mesotrophic range (10 < [P] < 20 μg P/l) suggesting that even the most aggressive nutrient reduction strategies will have limited success in improving water quality beyond mesotrophy. A similar result was found by Reavie et al. (2002) where historically inferred [P] of a number of southeastern Ontario lakes was in the same mesotrophic range. However, measured [P] in northwestern Pennsylvania lakes was on average about 2.2 times greater than predicted [P] based on assumed historical land cover, so in most cases considerable water quality improvement is possible. In the case of Conneaut Lake, predicted historical [P] is approximately 30% lower than current measured [P], and a TMDL that sets a 30% reduction in [P] as a lake remediation target is probably overly optimistic given current lake restoration strategies, and the current intense recreational use of the lake.

There are at least two limitations to our assumptions of pre-settlement forest cover. The first is the unknown influence of Native American horticulture. Although populations of Native Americans have been assumed to be small and their impact negligible, Ekdahl et al. (2004) convincingly demonstrate that a modest population of Iroquois near Crawford Lake, Ontario was sufficient to initiate marked changes in the lake's trophic status. It is unknown if similar settlements existed adjacent to northwestern Pennsylvania lakes although they have been recorded along area streams. The second is the extent of beaver-created wetlands along influent streams that may have served as natural sediment traps reducing the amount of P exported even from intact forested ecosystems. Naiman et al. (1986) have documented beaver dams in low-productivity boreal ecosystems at a mean density of 10.6 dams/km, and retaining between 35 and 6500 m^3 sediment per dam. Such sediment storage also traps a considerable mass of phosphorus that would otherwise be exported to lakes.

There are many small, regionally-important lake districts where there is considerable public interest in maintaining or improving water quality. Remediation targets set without knowledge of historical conditions may misdirect funds and energies toward unattainable goals. The use of regionally-specific P export models based on land cover offers an additional method to estimate the historic trophic status of these lakes that may be particularly useful in areas where cultural impact has made it impossible to create a calibration set based on diatom analysis that encompasses the range of expected historical conditions.

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References

Adams, J. T., 1931. The Epic of America. Little, Brown, and Co, Boston, 433 pp.

Allan, J. D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology and Systematics 35: 257–284.

Bennion, H., P. Johnes, R. Ferrier, G. Phillips & E. Haworth, 2005. A comparison of diatom phosphorus transfer functions and export coefficient models as tools for reconstructing lake nutrient histories. Freshwater Biology 50: 1651–1670.

Brenner, M., T. J. Whitmore & C. L. Schelske, 1996. Paleolimnological evaluation of historical trophic state conditions in hypereutrophic Lake Thonotosassa, Florida, USA. Hydrobiologia 331: 143–152.

Carlson, R. E., 1977. A trophic state index for lakes. Limnology and Oceanography 22: 361–369.

Daly, K., P. Mills, B. Coulter & M. McGarrigle, 2002. Modeling phosphorus concentrations in Irish rivers using land use, soil type, and soil phosphorus data. Journal of Environmental Quality 31: 590–599.

Dillon, P. J. & W. B. Kirchner, 1975. The effects of geology and land use on the export of phosphorus from watersheds. Water Research 9: 135–148.

Ekdahl, E. J., J. L. Teranes, T. P. Guilderson, C. L. Turton, J. H. McAndrews, C. A. Wittkop & E. F. Stoermer, 2004.

Prehistorical record of cultural eutrophication from Crawford Lake, Canada. Geology 32: 745–748.

Environmental Systems Research Institute., 2004. ArcGIS Version 9. ESRI, Redlands, CA.

Hamel, P. B., & E. R. Bruckner, 1998. How far could a squirrel travel in the treetops? A prehistory of the Southern forest. Transactions of the 63rd North American Wildlife and Natural Resources Conference, 309–314.

Heathwaite, L., A. Sharpley & W. Gburek, 2000. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. Journal of Environmental Quality 29: 158–166.

Hynes, H. B. N., 1975. The stream and its valley. Verh. Internat. Verein. Limnol. 19: 1–15 (Internationale Vereinigung fur Theoretische und Angewandte Limnologie).

Johnes, P. J. & A. L. Heathwaite, 1997. Modelling the impact of land use change n water quality in agricultural catchments. Hydrological Processes 11: 269–286.

Knowlton, M. F., M. V. Hoyer & J. R. Jones, 1984. Sources of variability in phosphorus and chlorophyll and their effects on use of lake survey data. Water Resources Bulletin 20: 397–407.

Krug W. R., W. A. Gebert, D. J. Graczyk, D. L. Stevens, B. P. Rochelle & M. R. Church, 1990. Map of mean annual runoff for the northeastern, southeastern, and mid-Atlantic United States, water years 1951–1980. U. S. Geological Survey Water-Resources Investigations Report 88-4094. U. S. G. S. Madison, Wisconsin, 12 pp.

Little, J. L., R. I. Hall, R. Quinlan & J. P. Smol, 2000. Past trophic status and hypolimnetic anoxia during eutrophication and remediation of Gravenhurst Bay, Ontario: comparison of diatoms, chironomids, and historical records. Canadian Journal of Fisheries and Aquatic Sciences 57: 333–341.

Mattson, M. D. & R. A. Isaac, 1999. Calibration of phosphorus export coefficients for total maximum daily loads of Massachusetts lakes. Journal of Lake and Reservoir Management 15: 209–219.

Naiman, R. J., J. M. Melillo & J. E. Hobbie, 1986. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). Ecology 67: 1254–1269.

Nürnberg, G. K., 1998. Prediction of annual and seasonal phosphorus concentrations in stratified and polymictic lakes. Limnology and Oceanography 43: 1544–1552.

Ostrofsky, M. L., 1978. Modification of phosphorus retention models for use with lakes with low areal water loading. Journal of the Fisheries Research Board of Canada 35: 1532–1536.

Pennsylvania Department of Environmental Protection, 2001. Conneaut Lake TMDL for nutrients. Unpublished report by PaDEP, Northwest Regional Office, Meadville, PA, 24 pp. Available on-line at http://www.dep.state.pa.us/watermanagement_apps/tmdl.

Reavie, E. D., R. I. Hall & J. P. Smol, 1995. An expanded weighted-averaging model for inferring past total phosphorus concentrations from diatom assemblages in eutrophic British Columbia (Canada) lakes. Journal of Paleolimnology 14: 49.

Reavie, E. D., J. P. Smol & P. J. Dillon, 2002. Inferring long-term nutrient changes in southeastern Ontario lakes: comparing paleolimnological and mass balance models. Hydrobiologia 481: 61–74.

Reckhow, K. H., M. N. Beaulac & J. T. Simpson, 1980. Modeling phosphorus loading and lake response under uncertainty: a manual and compilation of export coefficients. U. S. Environmental Protection Agency Report 440/5-80-011. U.S. EPA, Washington DC, 214 pp.

Sachs, H. M., T. Webb & D. R. Clark, 1977. Paleoecological transfer functions. Annual Review of Earth and Planetary Sciences 5: 159–178.

Strickland, J. D. H. & T. R. Parsons, 1968. A practical handbook of seawater analysis. Fisheries Research Board of Canada Bulletin 167, Ottawa.

United States Environmental Protection Agency, 2002. http://www.oaspub.epa.gov/waters/state_rept.control?p_state = pa.

United States Geological Survey, 2000. National Land Cover Data. Edition 1. USGS. http://www.mcmcweb.er.usgs.gov/catalog/metadata/usgs_nlcd_metadata.html.

Whitney, G. G. & J. P. DeCant, 2003. Physical and historical determinants of the pre- and post-settlement forests of northwestern Pennsylvania. Canadian Journal of forest Research 33: 1683–1697.

Zar, J. H., 1974. Biostatistical Analysis. Prentice-Hall, Inc, Englewood Cliffs, NJ, 620 pp.