Limnol. Oceanogr., 58(3), 2013, 945–950

doi:10.4319/lo.2013.58.3.0945

The extent that natural lakes in the United States of America have been changed by cultural eutrophication

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Abstract

We used paleolimnological data for 240 lakes from the U.S. Environmental Protection Agency's (USEPA) 2007 National Lakes Assessment to estimate the extent that natural lakes in the coterminous United States have been changed by anthropogenic activities. In order to detect cultural eutrophication, we analyzed data on diatom-inferred concentrations of total nitrogen (TN), total phosphorus (TP), specific conductance (SC), and pH as determined from lake sediments from the tops and bottoms of sediment cores from 240 natural lakes where the bottom of the core was judged to represent conditions prior to European settlement. We found no statistically significant increases in the average concentrations of TN, while TP decreased by 14% in this population of lakes since the time of European settlement. We also analyzed data from 48 reference lakes used by the USEPA to determine the relative condition of the sample lakes. Paired *t*-tests showed the TN concentrations were not significantly different between the two time periods ($p > 5\%$), while the average TP concentrations had significantly decreased by 26% since presettlement times ($p < 5\%$). There were statistically significant increases in SC (17%) and pH (0.05 pH units). There were no statistically significant differences between the changes in TP, TN, SC, and pH in the 240 sample lakes and the changes in the 48 reference lakes. The proportions of lakes categorized as oligotrophic, mesotrophic, eutrophic, and hypereutrophic for the presettlement time period were not significantly different from the proportions found in 2007.

There are many documented cases of individual lakes in the United States (such as Lake Erie and Lake Washington) that have changed in the past due to anthropogenic increases in loads of total phosphorus (TP) and/or total nitrogen (TN). Point sources such as wastewater treatment plants have been the major sources of accelerated eutrophication; however, following recent pollution control efforts, these sources have been controlled, and focus has been placed on nonpoint sources (National Research Council 1992) that are not as easily evaluated. For this reason, there have been few scientific estimates of the extent of changes in the chemical characteristics of natural lakes in the United States.

For regulatory purposes, the U.S. Environmental Protection Agency (USEPA) suggests that the nutrient concentrations of 75% of U.S. lakes are above their natural levels. For lakes with no or little development in their watersheds (reference lakes), they consider 25% of these lakes to have levels of TP and TN that have been elevated above their natural concentrations. We wished to test this hypothesis. The objective of this study is to use newly available data from the National Lakes Assessment (USEPA 2010*a*) to estimate the extent that natural lakes in the United States have been changed by anthropogenic activities.

Methods

The data analyzed in this study were collected as a part of the National Lakes Assessment (NLA) of 2007, which was conducted by the U.S. Environmental Protection Agency (USEPA 2010*a*). The survey used a probabilistic sampling procedure to select 1028 natural and manmade lakes that would be representative of the population of United States lakes larger than 0.04 km^2 in area, $\geq$ 1 m deep, and having $\geq$ 0.001 km^2 of open water. Lakes in Alaska and Hawaii and the Laurentian Great Lakes were not included. The survey was to provide a statistically valid picture of the condition of the lakes of the United States in 2007, and the results of the survey were published as a report to the U.S. Congress (USEPA 2010*a*) with links to the data sets for independent analyses (http://water.epa.gov/type/lakes/NLA_data.cfm). A technical appendix (USEPA 2010*b*) provides more detailed information on the conceptual basis and the methods and procedures used for the survey.

Because the goal of the NLA was to obtain an extensive picture of a large group of lakes rather than intensive studies on individual lakes, the USEPA visited most lakes only once in the summer of 2007. Of the wide variety of data collected on each lake, we have made use of the paleolimnological data collected from short sediment cores from the natural lakes. This approach has been applied in other regional lake surveys (Hall and Smol 1996; Dixit et al. 1999), and because the details of the sampling program are discussed in USEPA (2010*a,b*), we present only a brief summary of the procedure. A short sediment core was taken from each natural lake, and slices of the sediments from the tops and the bottoms of the cores were prepared for microscopic examination of the diatoms. The relative abundance of each species of diatom in each slice was tabulated. The diatom data for the surface samples at the tops of each core were used with the measured concentration of TP in that lake to find the relationship (transfer function) between diatom composition and TP concentration. This transfer function was then used to calculate the

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diatom-inferred concentration of TP at the top and bottom of each core. Similar analyses were used to find the diatom-inferred concentrations of TN, specific conductance (SC), and pH.

The USEPA (2010*b*) used a series of criteria to evaluate each core to determine their confidence (Yes, No, or Uncertain) that sediments at the bottom of the core represented a time prior to European settlement for the region in which the lake was located. For our analyses, we used core data only from those natural lakes with a confidence rating of 'Yes' and with inferences for both the tops and bottoms of the cores.

In addition to the lakes selected for probabilistic sampling, the USEPA (2010*b*) selected additional lakes from each of 11 nutrient ecoregions to serve as reference lakes (Stoddard et al. 2006). These were selected because they had a minimum amount of disturbance in their watersheds and were considered representative of the least-disturbed condition for lakes in their region. Least-disturbed condition was defined as the best available chemical, physical, and biological habitat conditions given the current state of the landscape—or 'the best of what's left' (Stoddard et al. 2006). The candidate reference lakes for chemical variables were screened to remove lakes that had low levels of acid-neutralizing capacity and dissolved organic carbon and high levels of chloride, sulfate, and shoreline disturbance by various anthropogenic activities. The remaining lakes were then used as a reference to compare with the sampled lakes. Of the 288 natural lakes with cores that were judged to reach presettlement conditions, 240 were sample lakes and 48 were reference lakes.

For each core, we subtracted the diatom-inferred concentrations of TP, TN, SC, and pH at the bottoms of the cores from their concentrations at the tops of the cores to find the magnitude and direction of any differences. To normalize these values, we used logarithms to the base 10 for the concentrations of TP, TN, and SC in our calculations; pH values were not transformed. For each of the four variables, we used paired *t*-tests (Sokal and Rohlf 1995) to determine whether the average differences were significantly different from zero. For this test and all other statistical tests, we used a 5% probability level to determine significance. We also used *t*-tests to determine whether the changes for each of the four chemical variables in the reference lakes were different from the changes in the sample lakes.

To determine the sensitivity of the paired *t*-tests, we used the standard deviations of the 240 differences for our error estimates. We found the standard error of the difference by dividing the standard deviation by the square root of the degrees of freedom (239). The 95% confidence interval was found by multiplying the standard error of the difference times 1.96 (the *t*-value for $p = 0.05$ with 239 degrees of freedom). Because we used a logarithmic transformation for TP, TN, and SC, the antilogs of the confidence limits were used to calculate the 95% confidence limits as percentages of the diatom-inferred values at the bottom of the sediment cores.

To determine whether the trophic states of the sample lakes had changed from presettlement times to the present, we used the trophic classification system of Forsberg and Ryding (1980) with diatom-inferred concentrations of TP to classify lakes into the categories of oligotrophic (TP $<$ 15 μg L^{-1}), mesotrophic (TP 15–25 μg L^{-1}), eutrophic (TP 25–100 μg L^{-1}), and hypereutrophic (TP $>$ 100 μg L^{-1}). This was done for the diatom-inferred TP concentrations at both the tops and bottoms of the cores. Chi-square analysis was used to determine whether there were significant differences in the proportions in each category between the sediments representing presettlement and current times.

Table 1. Standard deviations (SD), standard errors of the average differences (SE_{diff}) between top and bottom diatom-inferred concentrations of $\log_{10}$ total phosphorus (TP), $\log_{10}$total nitrogen (TN), $\log_{10}$ specific conductance (SC), and pH for 240 lakes and 95% confidence limits for the average differences. For TP, TN, and SC, the confidence limits are based on a percent of the untransformed variable at the bottom of the sediment core.

Variable	SD	SE_{diff}	95% confidence range
TP	0.33	0.021	−9.2–10.1
TN	0.21	0.013	−5.9–6.3
SC	0.22	0.014	−6.3–6.7
pH	0.35	0.023	−0.4–0.04 pH units

The USEPA (2010*a*,*b*) used TP and TN concentrations in the reference lakes for each of the nutrient ecoregions to set the standard for the sample lakes in that region. The assumption was made that, at the present time, 75% of the reference lakes can be categorized as Good, the next 20% of lakes can be categorized as Fair, and 5% of the reference lakes can be categorized as being in Poor condition. The TP and TN concentrations that formed the boundaries between the three categories in each nutrient region were used to place the sample lakes in that region into the above three categories. We used the same thresholds in each nutrient region to categorize the condition of the lakes in the present and presettlement times based on the diatom-inferred concentrations of TP and TN at the tops and bottoms of the sample lake cores and found the proportions of the sample lakes that fell in each category. Chi-square analyses were used to determine whether there were significant differences in the proportions in each category between the sediments representing presettlement times and current times.

Results

The use of paired *t*-tests with a large sample size of lakes enabled us to detect changes in the population averages of the diatom-inferred values from about 7% to 10% of the presettlement concentrations depending on the variable under study (Table 1). The frequency distributions of the changes in the diatom-inferred estimates for TP, TN, SC, and pH from the presettlement period to 2007 are similar to normal curves (Fig. 1), and the results of the paired *t*-tests indicate statistically significant decreases in TP in both the sample lakes (−14.1%) and the reference lakes (−26.4%) and statistically significant increases in SC of 17.5% in the sample lakes and 24.5% in the reference lakes (Table 2). The average increase in pH of 0.05 units in the sample lakes was statistically significant, but the change in the reference

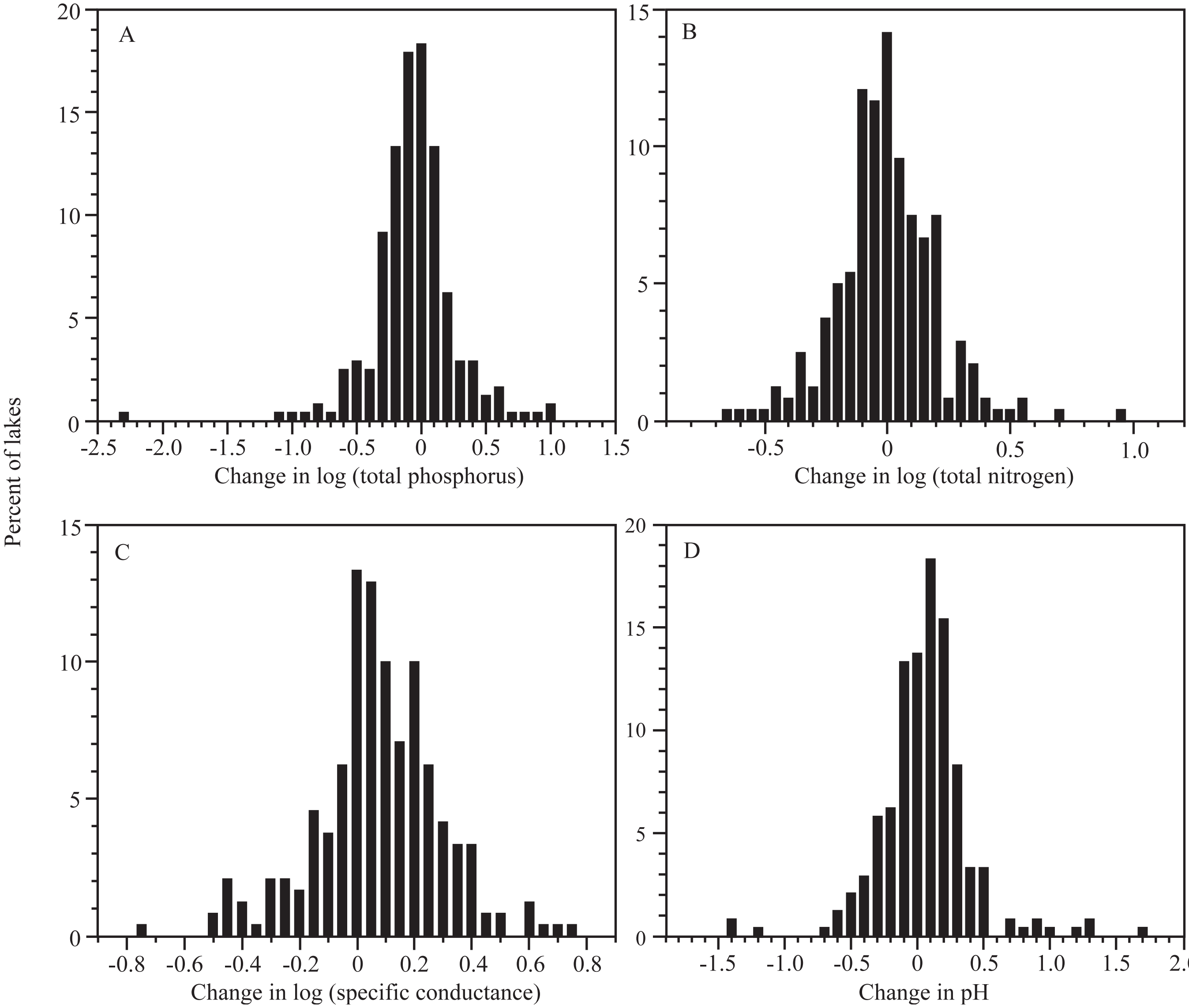

Fig. 1. Distributions of the changes in the diatom-inferred concentrations of (A) total phosphorus, (B) total nitrogen, (C) specific conductance, and (D) pH between the presettlement period and 2007 from a probabilistic sampling of lakes in the United States. Data are from USEPA (2010*a*).

lakes for pH was not. The changes in TN in both the sample and reference lakes were not statistically significantly different from zero. There were no statistically significant differences between the average changes in TP, TN, SC, and pH in the sample lakes and the average changes in the reference lakes (Table 2).

The diatom-inferred concentrations of TP were used to place lakes in the trophic categories of oligotrophic, mesotrophic, eutrophic, and hypereutrophic for the presettlement time period and the recent 2007 time (Fig. 2). Chi-square analyses on the numbers of lakes in each category for the two time periods showed no statistically significant difference in the proportions. This analysis indicates that the sample lakes have not become more eutrophic since European settlement.

We used the diatom-inferred concentrations of TP and TN at the tops and bottoms of the short cores to place the sample lakes in the categories of Good, Fair, and Poor following the procedures used by the USEPA (Fig. 3). We found that not all of the lakes were considered to be in the Good category prior to European settlement. For that time, 35% of the lakes based on TP would be placed in the Fair to Poor categories, and 25% based on TN would be in the Fair to Poor categories. A Chi-square analysis also showed that, for TP, there was an increase in the proportion of lakes in the Good category in 2007 compared with the presettlement time period. The difference was statistically significant. The same analysis for TN showed that there was no statistically significant difference in the proportions of lakes in each category between the two time periods.

Discussion

For the population of U.S. lakes as a whole, this analysis found no indication that there has been a large-scale

Table 2. Average changes in the diatom-inferred concentrations of $\log_{10}$ total phosphorus (TP), $\log_{10}$ total nitrogen (TN), $\log_{10}$ specific conductance (SC), and pH during the period from presettlement times to 2007 for the 240 sample lakes and the 48 reference lakes. Positive numbers indicate an increase in the values over time. For TP, TN, and SC, the changes in $\log_{10}$ units are converted to percents and shown in parenthesis. The last column gives the probabilities that the changes for the sample lakes are not different from the changes in the reference lakes.

Variable	Sample lakes (%)	Reference lakes (%)	Probability
TP	−0.066*(−14.1)	−0.133*(−26.4)	0.20
TN	−0.006(−1.4)	−0.026(−5.8)	0.53
SC	0.070*(17.5)	0.095*(24.5)	0.50
pH	0.052*	0.024	0.60

* The change is significantly different from 0 with $p = 0.05$.

increase in the concentrations of TP and TN in the time period from presettlement to 2007. The results of paleolimnological analyses of short sediment cores from 240 U.S. natural lakes show no statistically significant change in the concentrations of TN and a small decrease in the concentrations of TP. Although some lakes do show statistically significant increases or decreases in TP and/or TN in this time period, most lakes have not changed. This analysis indicates statistically that, on average, the sample lakes have not become more eutrophic since European settlement, contrary to the belief of many scientists and the USEPA (2000).

The proportions of lakes in the United States in the categories of oligotrophic, mesotrophic, eutrophic, and hypereutrophic are no different in 2007 from what they were prior to European settlement. Because these findings are based on sediment cores, they apply only to natural lakes and cannot be extended to manmade lakes or flowing waters.

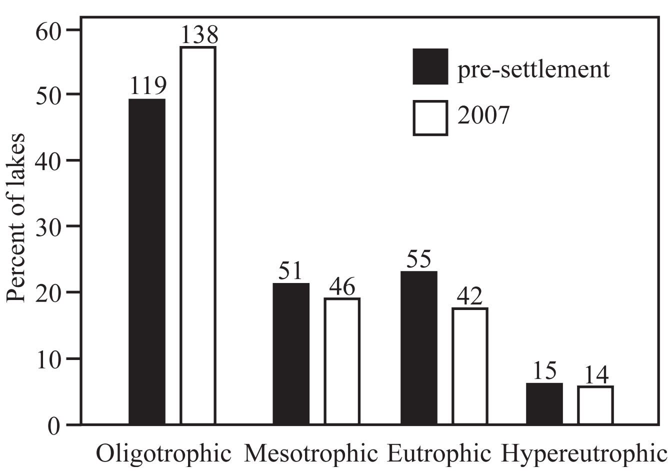

Fig. 2. Percents of lakes in four trophic categories based on diatom-inferred concentrations of total phosphorus in the tops and bottoms of short sediment cores for 240 lakes sampled in the National Lakes Assessment in 2007 (USEPA 2010*a*). Numbers above the bars indicate numbers of lakes. A Chi-square test showed no statistically significant difference ($p = 0.41$) between the distributions of lakes in the different trophic state categories for the two different time periods.

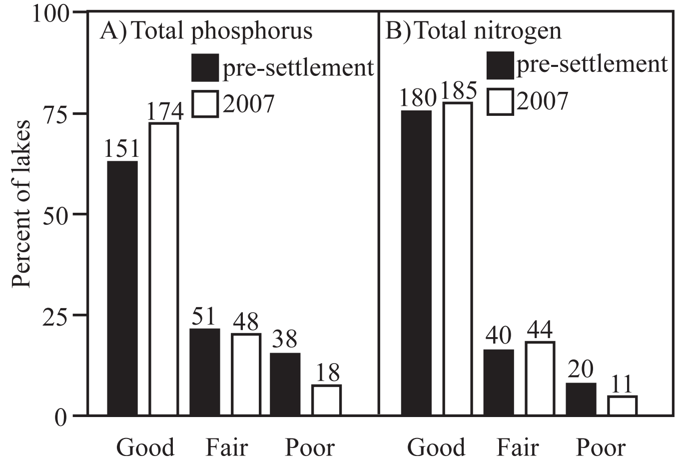

Fig. 3. (A) Percents of lakes in the categories Good, Fair, and Poor based on diatom-inferred concentrations of total phosphorus at the tops and bottoms of short sediment cores for 240 lakes sampled in the National Lakes Assessment in 2007 (USEPA 2010*a*). Placement of the lakes in the categories was based on the distributions of the concentrations of TP in the reference lakes for the nutrient region in which a lake was located. (B) The same plot for TN. Numbers above the bars indicate numbers of lakes. For TP, a Chi-square test showed a statistically significant difference ($p = 0.02$) between the distributions of lakes in the different categories for the two different time periods. There was no statistically significant difference ($p = 0.33$) for TN.

The interpretation of short core data in terms of cultural eutrophication is complicated by various sources of variability, as illustrated by our finding that almost as many lakes show an increase in their concentrations of TP and TN as do the numbers of other lakes that show a decrease from the bottom to the top of the cores. Part of this is because we have only two points on a data set of 100+ yr of nutrient concentrations that is subject to fluctuations due to natural factors such as climatic cycles. For example, Magnuson et al. (1997) presented data showing both short-term and long-term fluctuations in temperature, precipitation, and lake water levels for the Laurentian Great Lakes region over the past 100 yr. These are variables that can lead to changes in lakes. Hoyer et al. (2005) found that in one group of Florida lakes, increases in water levels were correlated with increases in TP, TN, or chlorophyll *a*, while another group of lakes showed no change, and a third group had decreases in these trophic states indicators as water levels increased. So, even if a lake has no anthropogenic acceleration of nutrient loadings over time; random events or the effects of climatic cycles will lead to either positive or negative changes for an individual lake from year to year. Shallow lakes may show changes in nutrient concentrations due to natural changes in macrophyte standing crops. Further, there will also be normal random sampling errors of measurement that cannot be estimated in this study, because there was no replication of the cores in individual lakes. These errors will tend to average out for the entire data set, but make it difficult to determine whether accelerated nutrient loading has affected an individual lake.

The reference lake approach used in our analysis differs from that used in the USEPA (2010*a*) report. Stoddard et al. (2006) defined the biological reference condition of an ecosystem as referring to the 'naturalness' of the biota (structure and function), and he stated that it implies an absence of significant human alteration. For our analysis, we used what he termed the 'historical condition.' That is, we used paleolimnological estimates of the conditions in each of the sample lakes prior to European settlement as our historical reference group, rather than the current chemical conditions in a separate group of lakes thought to be representative of the least disturbed lakes in that nutrient region. Thus the number of historical reference lakes was equal to the number of sample lakes, and the same random process used to select the sample lakes selected the reference lakes. The comparison of nutrient concentrations inferred for the presettlement and current times in the same lakes controlled for original differences among lakes due to natural factors.

The USEPA (2010*a*) used a different reference-lake approach with the same lakes and came to a different set of conclusions on the condition of U.S. lakes for TP and TN; 42% of the sample lakes were in the Fair to Poor categories for TP and 46% in the Fair to Poor categories for TN. They selected the reference lakes in each nutrient ecoregion on the basis of what Stoddard et al. (2006) called the 'least disturbed condition' or what the USEPA (2010*b*) called the best of what is left. They then used the distributions of chemical variables in the reference lakes as a standard of comparison for the other nonreference lakes in the same region. For example, the cumulative distribution of TP measurements in 2007 in the water samples from the reference lakes in a region is determined. The lakes in the lowest 75% of those reference lakes are considered to be in Good condition. The next 20% (i.e., 75th to 95th percentiles) are categorized as Fair and those in the top 5% are considered to be in Poor condition. The TP concentrations at the 75th and 95th percentiles are then applied to the nonreference lakes in that region to determine the distribution of Good, Fair, and Poor lakes (USEPA 2010*a*).

The unstated assumption of the reference lake approach as used in the NLA (USEPA 2010*a*) is that all lakes were in a Good condition prior to anthropogenic development. Another assumption is that the current reference lakes are a representative sample of the lakes in that region, and at the present time 25% of the reference lakes have had measurable increases in TP and or TN above the predisturbance levels. It is further assumed that the distribution of TP and TN in the reference lakes can be used to categorize the nonreference lakes as Good, Fair, or Poor, reflecting cultural eutrophication.

Our findings contradict those assumptions. When we applied the proportions of lakes that fell in the three categories based on the reference lakes to the inferred concentrations of TP and TN prior to European settlement, we found only 63% of the lakes were classified in the Good category for TP and 73% classified in the Good category for TN. Further, the proportions in the three categories based on TN were the same for the presettlement period as the 2007 period. In 2007, the proportion of lakes in the Good category based on TP had actually increased over the proportion prior to European settlement.

These results indicate that the reference lakes selected by the USEPA (2010*b*) may not be representative of natural conditions in the population of lakes within the region in which they are located and thus would not provide a valid standard by which to evaluate changes in the nonreference lakes. One problem might involve the way the reference lakes are selected. In a controlled experiment, there is a random assignment of test subjects to the control or test groups in order to keep the two groups as identical as possible at the beginning of the experiment. This increases the reliability of the results by minimizing the effects of variables other than the independent variable being studied. With the U.S. lakes studied it was not possible to randomly assign the lakes to the reference and nonreference groups prior to development in their watersheds. It was necessary to assume that in the process of selecting the lakes in the least disturbed condition, they were initially no different from those lakes with various types of anthropogenic activities surrounding them. In our opinion, this assumption would be violated in a region where variations in soil fertility and topography determined which watersheds were developed for agriculture and other human uses and which watersheds were not developed. Additionally, it is possible that lakes in unique rather than typical watersheds were more likely to be protected in state and national parks or reserves and thus be candidates as reference lakes. There is also the possibility of bias in the handpicking of the reference lakes, which might exclude naturally eutrophic lakes over lakes with lower nutrient concentrations.

There is also a problem if a nutrient ecoregion is drawn to encompass lakes with a large amount of natural variability. For example, the 7700 lakes in the state of Florida naturally range from oligotrophic to hypereutrophic (Bachmann et al. 2012) and have been grouped into 47 Lake Regions by the USEPA (Griffith et al. 1997). These Florida lake regions have been aggregated into six TP zones with statistically significant differences in average concentrations of TP (Bachmann et al. 2012). In the NLA, the Florida lakes are represented by only 1 lake out of the 14 reference lakes for the Coastal Plains nutrient ecoregion (USEPA 2010*b*) used for the determining lake condition with respect to TP and TN. This ecoregion is very large and includes lakes in a band along the U.S. east coast extending from New Hampshire to Texas, as well as lakes of the alluvial plain of the Mississippi River up to the Ohio River. Nine of the 14 reference lakes chosen for this ecoregion are located in the New England states. In our opinion, the reference lakes chosen for the Coastal Plains nutrient ecoregion are not representative of the diversity of the lakes of the region.

There are no other paleolimnological surveys based on a probability sample of the population of all U.S. lakes that can be used for comparison with our results; however, there was a similar survey of lakes in the northeastern United States (Dixit et al. 1999). That study also used the diatom-inferred concentrations of TP to compare pre-European settlement concentrations with recent ones in 139 natural lakes. The numbers of lakes falling in the classifications of oligotrophic, mesotrophic, and eutrophic were 66, 68, and

5, respectively, prior to European settlement and 69, 64, and 6 currently in the period 1991–1994. The proportions are not significantly different according to a Chi-square test ($p = 0.89$). A paleolimnological survey of lakes in the state of Minnesota that was not based on a random sample of lakes showed some ecoregions with no changes in TP following European settlement, while some ecoregions did have some lakes that showed an increase in TP (Ramstack et al. 2004). A study of the population of lakes in the state of Florida, by Bachmann et al. (2012), using several different methods did not show widespread cultural eutrophication, though there are a small number of individual lakes that have been affected by anthropogenic activities.

Our study did not find significant increases since presettlement times in TP and TN for natural lakes in the United States as a group; however, this does not mean that there are not individual lakes or groups of lakes that have been altered due to anthropogenic nutrient additions. Their numbers are just not large enough to make a significant difference in the averages. We note that our results apply only to natural lakes in the United States and not to manmade lakes, flowing waters, wetlands, or estuaries. Our results indicate that, in the United States of America, the extent that natural lakes have been changed by cultural eutrophication does not seem to be large. The assumption of widespread cultural eutrophication for setting numeric nutrient criteria in lakes is not supported.

Acknowledgments

We thank the U.S. Environmental Protection Agency Office of Water and Office of Research and Development for making their data freely available for independent analyses. Two anonymous reviewers provided helpful suggestions that strengthened the manuscript.

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Associate editor: Ronnie Nøhr Glud

Received: 28 September 2012
Accepted: 20 February 2013
Amended: 22 February 2013