Expanding Sediment Diatom Reconstruction Model to Eutrophic Southern Minnesota Lakes

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PROJECT SUMMARY

Surface sediment samples from 24 shallow eutrophic (46-664 ppb total phosphorus) southwest Minnesota lakes were appended onto an existing 55 Minnesota lakes diatom calibration set to create a new 79 lake diatom training set with better representation of lakes in the Western Corn Belt Plains (WCBP) and Northern Glaciated Plains (NGP) and better reconstruction performance for total phosphorus values above 60 ppb. Relationships among 14 environmental and morphometric variables and 157 diatom species distributions in the new 79 lake training set were explored using canonical correspondence analysis, a multivariate ordination technique. Environmental variables that independently explained a significant portion of variation in species distribution were identified using forward selection. Total phosphorus (TP) was the most explanatory variable in the refined calibration set, followed by pH, maximum lake depth, color, chloride, conductivity, mean lake depth, lake area, and acid neutralizing capacity (ANC). A transfer function for inferring total phosphorus was generated from the 79 lake calibration set using weighted averaging regression and calibration with inverse deshrinking. Three lakes identified as outliers were removed from the 79 lake data set to create a total phosphorus transfer function covering a gradient spanning lakes from 8-197 ppb TP. The transfer function was applied to estimate historical water column total phosphorus from subfossil diatom assemblages in six sediment cores recovered from lakes in southwest Minnesota; the transfer function was also applied to subfossil diatom assemblages in five southern MN cores used by Ramstack *et al.* (2003). In each core, diatom-inferred TP from a contemporary sediment sample was compared to two samples deposited before regional European settlement to identify baseline or reference nutrient conditions in each lake. Most of the lakes are currently eutrophic to hypereutrophic with monitored and diatom-inferred TP of 100-200 ppb; several of the larger and deeper lakes are less impacted (Beaver, Duck, Fish). Pre-settlement conditions in the eleven lakes were generally meso- to eutrophic and often showed within-lake variability. Pre-settlement conditions in the eleven lakes fell into two groups. In six of the eleven lakes, mean pre-settlement TP ranged from 30-60 ppb (Duck, George, Beaver, Big Twin, Clear, and Shaokatan). Five of the lakes, Cottonwood (Cottonwood Co.), Bloody, Bass, Fish, and East Twin, have long been very productive systems with presettlement mean diatom-inferred TP of 60-110 ppb.

INTRODUCTION

Among the myriad of human-induced landscape changes, agriculture, hydromanagement, water removal, drainage and tiling, point source loadings, recreation, and industrial use have led to wide-spread impairment of US surface waters. For many bodies of water in North America, eutrophication has been the outcome, with ~50% of impaired lakes and ~60% of impaired rivers suffering from excess nutrient loading (Carpenter *et al.* 1998, Correll 1998). Developing sound management plans to improve impaired waters requires that we 1) know the modern sources of nutrients to a receiving water, and 2) have an understanding of the natural or background nutrient conditions of a lake or river. The former is normally determined through monitoring, whereas the latter information is available from either modeling or paleoecology.

Diatom calibration and training sets have become powerful tools for paleoecological reconstruction and monitoring of surface water quality. Over the past 15 years, statistical methods have been developed to reconstruct specific environmental parameters from diatom assemblages. Whereas earlier diatom-based methods provide qualitative measures of historical water chemistry or productivity using categorical indicator values (ter Braak and van Dam 1989, Agbeti 1992), the development of weighted averaging regression and calibration introduced a method of quantitative reconstruction of historical environmental variables (Birks *et al.* 1990a,b). The method uses transfer function developed from a training set of diatom assemblages and their relationship to select environmental gradients in modern lakes that independently explain the variation in species distribution. The transfer function is next applied to historical diatom assemblages in sediment cores to mathematically reconstruct specific environmental variables. The weighted averaging method is statistically robust and based on ecologically sound organismal responses (ter Braak and Prentice 1988, Birks *et al.* 1990b). This approach has been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), DOC, and salinity (e.g. Anderson 1989, Fritz *et al.*, 1991, 1999, Dixit *et al.* 1992; Hall and Smol 1992).

For inferring historical total phosphorus (TP), diatom-based reconstructions have been adopted as the most powerful tool at hand (Fritz *et al.* 1993, Anderson and Rippey 1994, Reavie *et al.* 1995, Rippey and Anderson 1996). In the Minnesota region, the most readily applied training set was developed by Ramstack (1999) from surface-sediment diatom assemblages from 55 Minnesota lakes of varying trophic status that were earlier cored for a regional mercury study (Engstrom *et al.* 1999). The application of Ramstack's training set has targeted "top-bottom" or modern vs pre-European reconstructions of environmental parameters in Minnesota lakes (Ramstack 1999, Heiskary and Swain 2002, Ramstack *et al.* 2003, in press). The 55 Minnesota Lakes training set has been further applied to other Minnesota lake sediment records (Edlund and Engstrom 2001, Kingston *et al.* 2004), may be subsampled for regional training set development (Kingston, pers. comm.), and project results have been used for the development of nutrient criteria in Minnesota lakes (Heiskary and Swain 2002). Although a primary use of this model is regional TP reconstructions, the model is limited in its applicability because of weaknesses with reconstructing phosphorus levels above 60-80 ppb. This is due to the lack of higher TP lakes in the training set, truncation of species distributions along the TP gradient (Anderson 1997), and lack of lakes from major Minnesota ecoregions. For these reasons the original training set will be amended to include 24 eutrophic to hypereutrophic lakes from the Western Corn Belt Plains

(WCBP) and Northern Glaciated Plains (NGP) that have elevated modern TP values (45-660 ppb TP). Second, we then apply the expanded model to top-bottom reconstructions on six newly cored lakes and on five previously cored southern Minnesota lakes (Ramstack *et al*. 2003).

METHODS-CORING, DATING, AND SUBSAMPLING

Twenty-four lakes in the WCBP and NGP were identified by the MPCA for potential inclusion in the model (Table 1). The lakes have modern TP values that range from 45 to 660 ppb TP and were designated as reference lakes in the MPCA 2002 lake monitoring program (Heiskary *et al*. 2003).

A surface sediment sample (0-2 cm or 0-4 cm) was collected in Fall 2002 from the central depositional basin in each lake with a gravity corer. Samples were digested in 30% H_2O_2 for 2 hours at 85˚C, cooled, and oxidation byproducts removed with six rinses with distilled water. Subsamples of rinsed material were dried onto coverslips, which were subsequently attached to microslides with Naphrax mountant.

Piston cores were collected from eight lakes in southwest Minnesota in May 2003. Cores were taken using a drive-rod piston corer equipped with a 2.4 m long, 7 cm diameter polycarbonate barrel (Wright 1991). Target lakes and core recovery are provided in Table 2. Cores were vertically transported to shore, and the top 15-30 cm of unconsolidated sediment removed with extrusion in 2-cm increments. The remaining core material was capped, sealed, and transported to 4°C storage.

Cores were subdivided into 1.4-m long sections for magnetic susceptibility logging on a Bartington MS2 core logging sensor with an automated trackfeed. Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols. Susceptibility measures were taken at 1-cm intervals, which integrated a signal over a 5-10-cm length of core. Data were spliced at core breaks for plotting. Following susceptibility logging, cores were split lengthwise, physically described, and digital images taken of each core section using a Geoscan digital core scanner. Following scanning, cores were returned to storage at 4°C.

Two to three downcore samples from each core were selected for measurement of unsupported ^{210}Pb using a high-resolution germanium well gamma detector and multichannel analyzer (Table 3). The presence of any unsupported ^{210}Pb in a core subsample would be an indication that the sample is dated at less than seven half-lives of ^{210}Pb, approximately 150 years, or from a time period of very high sedimentation that would mask an unsupported ^{210}Pb signal. From this analysis we determined whether downcore sediment levels were deposited before European settlement.

The uppermost core sample found with no unsupported ^{210}Pb and a second sample taken from sediments deposited ca 50 years earlier were processed for diatom analysis. Mean linear and bulk sedimentation rates calculated from the NGP and WCBP lakes in the Ramstack (1999) lake set were used to calculate a pre-1850 SW Minnesota linear sedimentation rate (2.17 +/- 0.32 mm/yr), which guided our downcore sampling. The time interval represented by two presettlement samples were selected to correlate with the 1750 A.D. and 1800 A.D. sampling levels used in the Ramstack (1999) 55 MN lakes analysis (see also Heiskary and Swain 2002, Ramstack *et al*. 2003, in press). Without more detailed dating analysis on each core, we can only be certain that the two presettlement samples are dated from greater than 150 years before present; we cannot assign a specific calendar date to those samples based on gamma analysis and magnetic susceptibility logging.

METHODS-ENVIRONMENTAL DATA

Contemporary water chemistry and physical measures were collected on three to five sampling dates between May and October 2002 from 24 lakes in southwest Minnesota and reported as mean epilimnetic (integrated 0-2 m sample) values (Table 4; see also Heiskary *et al*. 2003). Samples were collected and analyzed using standard techniques (Heiskary *et al*. 2003). Physical measures of lake and watershed morphometry were taken directly or from the Minnesota Department of Natural Resources (1968). The raw environmental data taken from the 24 southwest Minnesota lakes were combined with environmental data used in the development of the original 55 Minnesota lake diatom training set. Assembly of the 55 lake environmental data earlier involved Dan Engstrom (SCWRS) and Steve Heiskary (MPCA); both of these researchers were contacted to better understand the analytical methods and calculations used in assembling that environmental data set (Table 5). Differences in analytical methods and data reporting between the 24 and 55 lake data sets were reconciled to create the full 79 lake data set. The final 79 Minnesota lake data set includes the following environmental and physical variables: chl a, pH, total phosphorus, total nitrogen, alkalinity/ANC, chloride, conductivity, color, Secchi depth, ecoregion, maximum lake depth, mean lake depth, lake area, and watershed area (Table 4).

METHODS-DIATOM ANALYSIS

Diatom remains were counted in surface sediment samples from all 24 southwest Minnesota lakes. A total of 400 diatom valves were counted along up to six random transects on Naphrax-mounted microslides using either an Olympus BX5O or Leitz Ortholux light microscope fitted with full immersion optics capable of 875-1250X magnification and N.A.>1.30. Our analysis used the same enumeration criteria as Ramstack (2003), i.e. diatoms were counted when over 50% of the valve was present or when a distinct valve fragment was present (e.g., central area of *Amphora libyca* or valve end in *Asterionella formosa*). One sample (East Twin Lake, Lyon County) had poor preservation and only 226 valves were counted after six transects. Raw counts were converted to percent abundance relative to all diatom microfossils.

Diatom remains were also counted from three samples from each of six sediment cores. The uppermost sample from 0-2 cm represents contemporary lake conditions. Two downcore samples from each core represent "pre-European" settlement conditions in the lakes. The 52 cm sample from Bloody Lake (Murray County) was later determined to represent post-settlement preservation; a sample from 72 cm depth was thus added to the analysis to represent pre-European sedimentation in Bloody Lake.

Diatoms were identified using floras and monographs by Hustedt 1927-1966, 1930, Patrick and Reimer 1966, 1975, Collins and Kalinsky 1977, Camburn *et al*. 1978, 1984-1986, Krammer and Lange-Bertalot 1986, 1988, 1991a, b, Cumming *et al*. 1995, Reavie and Smol 1998, Camburn and Charles 2000, and Fallu et. al. 2000. Workshops were held between the labs at SCWRS and NRRI to coordinate and document the taxonomy used in developing the 55 lake and 24 lake diatom training sets. We critically reanalyzed the taxonomy used in the construction of the 55 lake training set (Ramstack 1999). Ramstack (1999) species counts were provided in a species-coded format; we decoded the list using the web-available DIATCODE (http://amphora.geog.ucl.ac.uk/), cross-referenced them against published names, TP optima, images, and actual specimens from both diatom data sets (Ramstack *et al*. 2003, Edlund unpublished). When taxonomic harmonization questions remained unresolved, surface sediment samples used in the 55 Minnesota lakes training set were recounted. The specific taxonomic conversions from the original Ramstack data set are available from MBE.

METHODS-NUMERICAL ANALYSIS

Relationships among environmental variables and species distributions for all 79 lakes in the training set were explored using canonical correspondence analysis (CCA), a multivariate ordination technique for direct gradient analysis (ter Braak & Prentice, 1988) available in the CANOCO 4 software package (ter Braak and Smilauer 1998). Species present at greater than 1% relative abundance in two or more samples or at greater than 5% relative abundance in one sample were included in ordination analyses; the same selection criteria were used by Ramstack *et al*. (2003). A total of 13 environmental variables (ecoregion omitted) and 157 species was included in the ordination analyses. Environmental data that were not normally distributed were log(x) or log(x+1) transformed (logx: color, TN, TP, lake area, Zmax, Zmean, watershed area; log(x+1): chloride, chlorophyll-a). The distribution of environmental variables and species among samples was initially explored with principal components analysis (PCA) and detrended correspondence analysis (DCA), respectively, to screen for outliers and determine gradient length. A CCA with forward selection was used to identify a subset of environmental variables that independently explained a significant portion of variance in the species data ($p<0.05$). For each environmental variable identified in forward selection a constrained CCA was run to test significance and percent variance explained. For all CCA ordinations, rare taxa were downweighted and Monte Carlo permutation run to test for significance. Environmental variables that independently explained significant variation in the species distributions can then be used as predictor variables to develop transfer functions using weighted averaging regression and calibration (Birks *et al*., 1990).

A transfer function for reconstructing logTP was developed using weighted averaging (WA) regression with inverse deshrinking and bootstrap error estimation (C2 software; Juggins 2003). The strength of the transfer function was evaluated by calculating the squared correlation coefficient (r^2) and the root mean square error (RMSE) between the observed logTP with the model estimates of logTP for all samples. Bootstrapping is used in model validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction) because the same data are used to both generate and test the WA model (Fritz *et al*. 1999). Outliers were identified from plots of model and bootstrap residuals; samples with residuals greater than the standard deviation of logTP (SD_{logTP}=0.47) in the training set were removed for development of the final transfer function. Reconstructed estimates of TP (diatom-inferred TP, or DI-TP) for each surface and downcore sample were determined by taking the logTP optimum of each species, weighting it by its abundance in that sample, and determining the average of the combined weighted species optima. Downcore reconstructions of environmental variables are strongest if the fossil assemblage is analogous to a modern sample in the training set. The software ANALOG 1.6 (Birks, unpublished) was used to calculate a minimum dissimilarity coefficient (DC) between each fossil sample and its nearest modern analogue using the squared chi-squared distance metric. A minimum DC of less than 0.6284 (the fifth percentile of distance distributions among the modern samples) identified a fossil sample with a good modern analogue.

RESULTS & DISCUSSION-ENVIRONMENTAL DATA

The 24 lakes (Fig. 1, Table 1) added to the existing 55 Minnesota lakes provide a much needed picture of the typical lake condition and diatom flora found in the WCBP and NGP ecoregions of Minnesota. These lakes typify the shallow (Zmean = 1.8m), eutrophic to hypereutrophic condition common in these two ecoregions. Modern conditions in each lake, an environmental synthesis, and a regional context have been presented in Heiskary *et al*. (2003). In general, the lakes are characterized by elevated nutrient concentrations (mean TP = 169 ppb) and poor water clarity (mean Secchi depth = 0.66m) from algal production (mean chlorophyll-a = 60 ppb) and frequent sediment resuspension. Many of the lakes have also experienced historical loss of macrophytes (Heiskary *et al*. 2003) with primary production now dominated by water column productivity.

RESULTS & DISCUSSION-CORING AND DATING

Piston cores were recovered from eight southwest Minnesota lakes (Fig. 1, Table 2). The core recovered from West Twin Lake (Lyon Co.) was deemed too short and rejected for further analysis; subsequent dating also led us to reject the core from West Graham Lake (see below). For all cores, magnetic susceptibility was plotted against downcore depth. Features in the magnetics profile were correlated with core scans and visual descriptions to identify major changes in historical sedimentation (see Appendix A Figs 1-7). In some cores, a clear magnetics peak due to increased erosional signal was evident, likely correlated to initial European land clearance was apparent (e.g. Bloody Lake, Appendix A-Fig 2). However, many of the lakes showed multiple magnetics peaks over the length of the cores (e.g. Big Twin, Appendix 1-Fig 1). Secondary magnetics spikes often correlate with paleosols formed during historical periods of lake drying and/or may reflect historical increases in aeolian deposition during more arid climate periods. Because of uncertainties for pre-European sediment recovery in the magnetic profiles, two to three subsamples were also analyzed for unsupported ^{210}Pb gamma analysis (Table 3; Appendix A-Figs 1-7). Apart from West Graham Lake, all other samples analyzed indicated that pre-European settlement sediments were recovered; unsupported ^{210}Pb levels were not significantly different from zero (Table 3, Appendix A-Figs 1-7).

The core taken in West Graham Lake (Nobles Co.) did not contain pre-European lacustrine sedimentation above 29 cm core depth (Appendix 1-Fig. 7). Below this core depth, sediments were more likely deposited during a period of lake drying or severe shallowing to the core depth of 70 cm. Basal sediments of the West Graham core were most likely early Holocene marls and clays. Following diatom analysis, the Bloody 52 samples was also determined to likely represent sediments deposited post-European settlement. Although the unsupported ^{210}Pb levels were not significantly different from zero, the Bloody52 sample was taken at a peak of magnetic susceptibility and was clearly located above the stratigraphic loss of macrophyte fossils in the core. To better represent pre-European conditions, Bloody72 was added to the diatom analysis.

RESULTS & DISCUSSION-MICROSCOPY AND DIATOM TAXONOMY

We encountered approximately 540 diatom taxa in the entire 79 lake data set (Ramstack and Edlund, unpublished data). During the course of analysis and through multiple workshops held between the SCWRS and NRRI labs, efforts were made to coordinate and harmonize the diatom taxonomy used in developing the earlier 55 lake training set (Ramstack *et al*. 2003) and the appended 24 lake data set. Images of dominant taxa in the combined data set were gathered for quality control and to facilitate future use of the training set (images available from Edlund or Kingston).

In general, the 24 surface sediment samples from the southwest Minnesota shallow lakes are dominated by planktonic diatoms that are indicators of eutrophic conditions. Mean relative abundance of planktonic diatoms in surface sediments across the region is 70% (n=24; Fig. 2). The plankton communities are generally dominated by eutrophic indicators such as *Aulacoseira granulata*, *A. ambigua*, *Stephanodiscus niagarae*, *S. minutulus*, *S. parvus*, and *Fragilaria capucina* v. *mesolepta* (Fig. 4, in part).

The diatoms preserved in six sediment cores record a general historical shift from benthic-dominated diatom assemblages to planktonic dominated assemblages (Fig. 3). The six lakes are surprisingly different in their specific historical responses. We see overall modern increases in *Aulacoseira ambigua*, *A. granulata*, *Stephanodiscus minutulus*, and *S. niagarae* among the cores (Fig. 4); however, not in all cores (e.g. Shaokatan). Benthic species show consistent modern decreases in abundance in most cores, especially the fragilarioid diatoms and the dominant *Navicula* and *Nitzschia* species (Figs 3, 4). A secondary observation on these shallow lake systems is that the diatom communities have been historically variable. In several cores, large variability in the presettlement diatom communities was apparent (e.g., Big Twin Lake, Figs 3, 4). Based on the six cores, regional planktonic relative abundance in the pre-settlement sediment record is approximately 40% (n=12; Fig. 3). Combining the six 0-2 cm core sections and the 24 surface sediment training set samples suggests that modern regional planktonic diatom abundance in sediment assemblages is approximately 67.2% (n=30, Fig. 3). This shift from benthic-dominated diatom communities to planktonic dominance is a classic response to regional increased in nutrient loading and eutrophication (Wetzel 2001, Moss 2003).

RESULTS & DISCUSSION-79 LAKES CALIBRATION SET AND TOTAL PHOSPHORUS TRANSFER FUNCTION

Results of the CCA indicated that the 13 environmental and physical variables collectively explain 35.9% of the variance in the species data with 11.3% and 6.7% of the variance explained by axes 1 and 2, respectively. Because of correlation among environmental variables, a CCA was run with forward selection and identified that the following nine variables, TP, pH, Zmax, color, chloride, conductivity, Zmean, lake area, and ANC, each independently explain significant variation in the species data, and together account for 32.1% of the variance in the diatom data or 89.4% of the variance explained by all environmental variables. Using a constrained CCA, the significance of each variable was tested ($p<0.05$). Total phosphorus was the most explanatory variable, independently accounting for 9.4% of the variance in the species data. The other eight environmental and physical variables and the percent variance explained included: pH (7.5%), Zmax (8.7%), color (3.9%), chloride (6.5%), conductivity (9.0%), Zmean (7.2%), lake area (5.3%), and ANC (7.9%).

A CCA biplot of the nine environmental variables identified with forward selection shows the high correlation of logTP with axis 1 (Fig 5). The environmental variables most strongly correlated with axis 2 are color, pH, and chloride. When all 79 Minnesota lakes are plotted in ordination space they cluster by ecoregion (Fig 5). Lakes from the WCBP and NGP are positioned on the right of axis one at the upper end of the TP and lake area vectors. TP was also strongly correlated with TN, chlorophyll-a (positive) and Secchi depth (negative), which were removed during forward selection. Lakes in the NCHF are centrally positioned in the ordination. Metro lakes cluster to the left on axis 1 and negative on axis 2, an indication of their modern mesotrophy and elevated chloride levels. Lakes of the NLF are clustered in the upper left of the ordination; this group characterized by low productivity, stained waters, and contain the lowest pH lakes in the data set.

Downcore sediment samples were treated as supplemental samples and their species assemblages passively graphed onto the ordination biplot (Fig. 5). Most upcore sediment assemblages and some pre-European sediments plotted within the cluster of modern NGP and WCBP lakes. Downcore assemblages generally plotted left (negative on the TP gradient) of their upcore or modern counterparts. Interestingly, a subset of pre-European sediments (Big Twin, Shaokatan, Clear) plotted outside of the cluster of modern NGP and WCBP lakes suggesting that the pre-European diatom assemblages in these lakes are quite different than any modern assemblages that were sampled.

Because TP was identified as the most explanatory environmental variable using CCA, it was available as a predictor variable to develop a mathematical transfer function to estimate logTP from modern or fossil diatom assemblages. Weighted averaging using inverse deshrinking (WA_{inv}) and bootstrap error estimation was chosen to develop the transfer function. Initial model results and error estimates based on all 79 lakes identified three lakes as outliers, (Dickman, George -Blue Earth Co., and Loon -Jackson Co.), which were removed from the final WA_{inv} model. The performance (Fig. 6) of the final TP model (76 lakes, 141 species) was evaluated using the squared correlation coefficient between observed and diatom-inferred total phosphorus ($r^2 = 0.849$) and the apparent root mean square error (RMSE = 0.175). Because the same samples are used to develop and test the model, bootstrapping is used for model validation and provides a more realistic error estimate, the root mean square error of prediction ($RMSEP_{boot} = 0.204$). Because averaging is used to in both the regression and calibration steps in transfer function development, weighted averaging models tend to overestimate low TP values and underestimate high TP values. Inverse deshrinking is thus used to correct initial reconstructed TP values. Initial inferred logTP values calculated with our transfer function were corrected with the following deshrinking equation:

$$\text{final logTP} = (\text{initial logTP})*(-0.738)+1.463$$

Calculated total phosphorus optima for the 141 species are presented with number of occurrences and maximum relative abundance in Table 6. Phosphorus optima ranged from 7.6 ppb to 197 ppb.

RESULTS & DISCUSSION-SEDIMENT CORE RECONSTRUCTIONS

The logTP transfer function was applied to downcore diatom assemblages in six sediment cores recovered in 2003 and five southern Minnesota sediment cores analyzed earlier by Ramstack *et al*. (2003) to calculate diatom-inferred total phosphorus (DI-TP). From each core, two samples representing sediments deposited before regional European settlement provide a measure of baseline or natural nutrient conditions in these lakes. Presettlement conditions can be compared to a DI-TP estimated from a third core sample (0-2 cm) representing modern conditions and to monitoring records collected by MPCA in 2002 or in the mid 1990s for the five southern lakes (Table 7).

Big Twin Lake, Martin Co. (MDNR 46-0133) had monitored TP of 141 ppb in 2002. Modern mean DI-TP was similar at 123 ppb. Modern TP values are over two times higher than pre-European condition in Big Twin Lake, which had a mean DI-TP of 57 ppb.

Bloody Lake, Murray Co. (MDNR 51-0040) produced somewhat confusing results in our analysis. Monitored in 2002 with a mean TP of 89 ppb, the reconstructed DI-TP was 169 ppb which is above even the highest monitored value in 2002 (121 ppb). Both samples analyzed for pre-European conditions in Bloody Lake were similar with a mean DI-TP of 69 ppb; however, both samples were without modern analogues.

Clear Lake, Jackson Co. (MDNR 32-0022) has experienced dramatic changes since pre-European times. Clear lake had the lowest pre-European DI-TP of all southern Minnesota lakes at 31 ppb. Mean monitored TP from 2002 was 110 ppb which compared well with our modern DI-TP of 89 ppb.

Cottonwood Lake, Cottonwood Co. (MDNR 17-0022) has likely been a very productive lake system for several centuries. Monitored in 2002 with a mean TP of 83 ppb, DI-TP of upcore sediments was 118 ppb. Pre-European sediments from Cottonwood Lake preserve a signal of similar historical productivity with DI-TP of 96 ppb.

East Twin Lake, Lyon Co. (MDNR 42-0070) has a similar sediment record of both modern and historical high phosphorus levels. Mean pre-European DI-TP was 98 ppb. Modern sediments had somewhat higher reconstructed DI-TP of 162 ppb; the modern DI-TP was notably higher than 2002 monitoring records that ranged from 84 to 121 ppb with a seasonal mean of 121 ppb.

Shaokatan Lake, Lincoln Co. (MDNR 41-0089) had a much lower pre-European nutrient condition compared to modern times. Mean pre-European DI-TP was 50 ppb; whereas modern DI-TP was 107 ppb. The modern DI-TP compared well to a mean TP of 124 ppb measured during the 2002 monitoring season.

DI-TP reconstructions using the 55 lake training set that were previously reported by Heiskary and Swain (2002) and Ramstack *et al*. (2003, in press) on the five southern Minnesota lakes are generally lower in pre-European sediments and slightly higher in modern sediments when compared to DI-TP reconstructions using the new 79 lake training set.

Bass Lake, Faribault Co. (MDNR 22-0074) had mean pre-European DI-TP of 73 ppb and had good analogues in the training set. Modern DI-TP was lower than pre-European at 52 ppb, which may be an underestimate as monitored mean TP in the 1990s was 81 ppb.

Beaver Lake, Steele Co. (MDNR 74-0023) has seen little change between pre-European and modern times. Pre-European TP levels were 54 ppb and modern levels are slightly lower with a DI-TP of 35 ppb and a 1990s monitored mean TP of 30 ppb

Duck Lake, Blue Earth Co. (MDNR 07-0053) tells a similar story to Beaver Lake with little historical change in nutrient levels. Mean pre-European DI-TP and modern DI-TP reconstructed at 41 ppb. Monitoring in the 1990s found TP levels of 65 ppb.

Fish Lake, Jackson Co. (MDNR 32-0018) has a significantly higher pre-European DI-TP using the 79 lake training set at 85 ppb. Ramstack (1999) also found very productive pre-European conditions with DI-TP reconstructions of 64 ppb. Modern Fish Lake had a 1990s monitored mean TP of 38 ppb compared to a 1990s DI-TP of 48 ppb.

George Lake, Blue Earth Co. (MDNR 07-0047) is a conundrum in this data set. It was identified as an outlier and removed during analysis to construct the final transfer function. Monitoring in the 1990s found TP levels of 130 ppb, but reconstructed modern DI-TP was only 30 ppb using the 79 lake training set compared to 37 ppb using the 55 lake training set. Pre-European DI-TP in George Lake was 59 ppb using the 79 lake transfer function.

Most of the lakes in southern and southwest Minnesota are currently eutrophic to hypereutrophic with monitored and diatom-inferred TP of 100-200 ppb (this study, Heiskary *et al*. 2003); several of the larger and deeper lakes are less impacted (Beaver, Duck, Fish). Pre-settlement conditions in the eleven lakes were generally meso- to eutrophic and often showed within-lake variability. Pre-settlement conditions in the eleven lakes fell into two groups. In six of the eleven lakes, mean pre-settlement TP ranged from 30-60 ppb (Duck, George, Beaver, Big Twin, Clear, and Shaokatan). Five of the lakes, Cottonwood (Cottonwood Co.), Bloody, Bass, Fish, and East

Twin, have long been very productive systems with presettlement mean diatom-inferred TP of 60-110 ppb.

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TABLES

Table 1. Names, Minnesota DNR designator, locations, and ecoregions of 24 southwest Minnesota lakes.

Lake	MN DNR Lake ID	County	Region
Bingham	17-0007	Cottonwood	WCBP
Cottonwood	17-0022	Cottonwood	WCBP
Talcott	17-0060	Cottonwood	WCBP
Loon	32-0020	Jackson	WCBP
Clear	32-0022	Jackson	WCBP
Dead Coon	41-0021	Lincoln	NGP
Benton	41-0043	Lincoln	NGP
Shaokatan	41-0089	Lincoln	NGP
East Twin	42-0070	Lincoln	NGP
West Twin	42-0074	Lincoln	NGP
School Grove	42-0002	Lyon	NGP
Cottonwood	42-0014	Lyon	NGP
Yankton	42-0047	Lyon	NGP
Rock	42-0052	Lyon	NGP
Goose	42-0093	Lyon	NGP
Big Twin	46-0133	Martin	WCBP
Lime	51-0024	Murray	WCBP
Bloody	51-0040	Murray	WCBP
Sarah	51-0063	Murray	NGP
Currant	51-0082	Murray	NGP
East Graham	53-0020	Nobles	WCBP
West Graham	53-0021	Nobles	WCBP
Curtis (Houston)	87-0016	Yellow Med.	WCBP
Wood	87-0030	Yellow Med.	WCBP

Table 2. Lakes cored in May 2003 and length of core recovered.

Lake Name	Lake ID	County	Core length (cm)
Big Twin	46-0133	Martin	173
Bloody	51-0040	Murray	133
Clear	32-0022	Jackson	78
Cottonwood	17-0022	Cottonwood	102
East Twin	42-0070	Lyon	107
Shaokatan	41-0089	Lincoln	85
West Graham	53-0021	Nobles	114 (rejected)
West Twin	42-0074	Lyon	60 (rejected)

Table 3. Unsupported ^{210}Pb quantified from select core depths from southwest MN lakes. Unsupported ^{210}Pb values that are negative or not significantly different from zero likely represent sediment deposited at greater than seven half-lives of ^{210}Pb or approximately 150 years.

Lake Name	Lake ID	County	Sample depth (cm)	Unsupported 210-Pb
Big Twin	46-0133	Martin	107-108	-0.8761
Big Twin	46-0133	Martin	167-168	-0.8719
Big Twin	46-0133	Martin	79-80	-0.929
Bloody	51-0040	Murray	51-52	-0.9474
Bloody	51-0040	Murray	64-65	-0.2132
Clear	32-0022	Jackson	57-58	-0.9361
Clear	32-0022	Jackson	77-78	0.0539
Cottonwood	17-0022	Cottonwood	95-96	-0.8996
Cottonwood	17-0022	Cottonwood	71-72	-0.8233
East Twin	42-0070	Lyon	67-68	-0.6569
East Twin	42-0070	Lyon	101-102	-0.5631
Shaokatan	41-0089	Lincoln	55-56	-0.5761
Shaokatan	41-0089	Lincoln	81-82	-0.2184
West Graham	53-0021	Nobles	16-17	1.8702
West Graham	53-0021	Nobles	25-26	1.2229

Table 4. Units and sources of environmental and physical data used in developing the 79 Minnesota lakes diatom training set.

Variable	unit/reference	55 MN lakes source	24 SW MN lakes source
chl a	µg/L	Ramstack *et al.* 2003*	2002 MPCA data from SAH**
pH	—	Ramstack *et al.* 2003	2002 MPCA data from SAH
total phosphorus	µg/L	Ramstack *et al.* 2003	2002 MPCA data from SAH
total nitrogen	µg/L	Ramstack *et al.* 2003	2002 MPCA data from SAH
alkalinity/ANC	meq/L	Ramstack *et al.* 2003	2002 MPCA data from SAH
chloride	mg/L	Ramstack *et al.* 2003	2002 MPCA data from SAH
conductivity	µS/cm	Ramstack *et al.* 2003	2002 MPCA data from SAH
color	Pt-Co	Ramstack *et al.* 2003	2002 MPCA data from SAH
secchi depth	m	Ramstack *et al.* 2003	MPCA data from SAH
ecoregion	Omerick 1987	Heiskary *et al.* 2002	Heiskary *et al.* 2003
maximum lake depth	m	Heiskary *et al.* 2002	Heiskary *et al.* 2003
mean lake depth	m	unpub LCMR data from SAH	Heiskary *et al.* 2003
lake area	ha	Heiskary *et al.* 2002	Heiskary *et al.* 2003
watershed area	ha	Heiskary *et al.* 2002	Heiskary *et al.* 2003

*Ramstack *et al.* (2003) data were taken directly from the publication; however, Dan Engstrom (SCWRS) provided the original spread sheets used in calculating these values.

**SAH=Steve A. Heiskary, Minnesota Pollution Control Agency

Table 5. The final 79 Minnesota lakes data set includes the following environmental and physical variables: pH, ANC, conductivity, color, chloride, total phosphorus, total nitrogen, chlorophyll-a, ecoregion, Secchi depth, , lake area, maximum lake depth, watershed area, mean lake depth.

Lake	Code	MN DNR ID	pH	ANC	Cond	Color	Cl	TP	TN	Chla	Eco-region	SD	lake area	Z max	Wshed area	Z mean
			SU	μeq/L	μS/cm	Pt-Co	mg/L	ug/l	ug/L	ug/L	USEPA	m	ha	m	ha	m
August	August	38-0691	7.25	290	40	96.73	0.9	15	440	2.42	NLF	1.58	76.5	5.8	937	2.5
Bass	Bass	22-0074	8.96	3338	343	20.15	15.0	81	1354	24.96	WCP	1.10	75.7	6.1	136	3.1
Bean	Bean	38-0409	7.64	526	53	8.48	0.3	17	283	6.59	NLF	1.89	12.5	7.9	64	4.6
Bear	Bear	38-0405	7.45	342	45	9.10	0.4	11	161	1.36	NLF	4.75	18.3	8.8	60	4.5
Beaver	Beaver	74-0023	8.86	2501	268	9.40	15.0	30	1123	12.23	WCP	1.37	37.8	8.2	71	4.4
Calhoun	Calhoun	27-0031	8.70	2150	547	9.00	117.0	28	791	5.78	Metro	3.94	168.5	27.4	2515	10.7
Carver	Carver	82-0166	8.70	2190	574	23.50	123.0	36	883	8.27	Metro	1.58	19.6	11.0	864	4.6
Christmas	Christmas	27-0137	8.90	2620	304	6.50	23.0	15	660	3.10	Metro	5.60	105.7	26.5	189	11.0
Diamond	Diamond	34-0044	8.55	3365	332	15.58	16.1	80	1400	33.82	NCHF	2.12	644.8	8.2	3590	4.8
Dickman	Dickman	19-0046	7.89	1480	310	13.33	58.0	105	1533	63.97	Metro	0.62	9.1	2.4	57	2.4
Duck	Duck	07-0053	8.91	2892	298	11.65	16.2	65	1190	44.52	WCP	0.87	116.6	7.6	385	3.0
Dunns	Dunns	47-0082	8.64	2232	291	15.26	17.5	139	1775	52.54	NCHF	0.83	63.0	6.1	1381	3.6
Dyers	Dyers	16-0634	7.57	690	72	68.58	0.8	27	406	3.25	NLF	1.78	27.8	6.1	854	2.8
Elmo	Elmo	82-0106	8.50	2870	303	8.00	17.0	10	485	2.82	Metro	2.70	114.6	42.7	2076	13.4
Fish (Dakota)	Fish_D	19-0057	7.59	1613	415	19.00	101.0	79	797	37.60	Metro	0.93	12.5	10.1	1506	1.8
Fish (Jack)	Fish_J	32-0018	8.82	3245	370	9.30	20.2	38	996	15.32	WCP	1.20	120.7	8.2	649	4.5
Forsythe	Forsythe	31-0560	6.89	233	32	84.58	0.7	21	702	5.41	NLF	2.04	27.1	3.1	191	1.8
George (BE)	George_B	07-0047	9.18	1982	220	25.10	11.2	130	2067	80.79	WCP	0.46	36.2	8.5	54	2.9
George (Kand)	George_K	34-0142	8.82	4548	450	4.79	28.4	15	627	3.16	NCHF	3.44	91.6	9.1	102	4.9
Gervais	Gervais	62-0007	8.32	2320	529	17.50	102.0	33	1100	16.30	Metro	2.00	94.4	12.5	4028	5.8
Harriet	Harriet	27-0016	8.90	2090	494	8.50	96.0	27	736	7.26	Metro	3.54	138.6	25.0	387	8.8
Henderson	Hendersn	34-0116	8.61	4176	410	7.08	17.6	22	896	4.58	NCHF	3.63	29.1	12.2	59	6.6
Hook	Hook	43-0073	8.44	2952	359	14.96	25.3	68	1788	23.26	NCHF	1.77	133.1	5.5	620	2.1
Johanna	Johanna	62-0078	8.25	1620	511	16.50	119.0	36	1000	13.89	Metro	2.45	86.4	12.5	1026	5.2
Kreighle	Kreighle	73-0097	8.50	2008	178	3.33	1.2	11	600	2.00	NCHF	4.20	41.0	17.1	88	5.2
Little Bass	L_Bass	31-0575	8.16	2421	209	16.62	1.8	13	406	2.93	NLF	4.43	64.5	18.9	540	7.6
Little Carnelian	L_Carnel	82-0014	8.80	2120	224	7.00	8.3	9	460	2.31	Metro	4.80	46.7	19.2	1854	3.9
Little Long	L_Long	27-0179-02	8.80	1680	184	9.00	3.7	9	440	2.18	Metro	5.09	21.8	23.2	32	18.7
Little Trout	L_Trout	69-0682	7.37	306	37	2.93	0.3	7	265	0.73	NLF	6.41	107.6	29.0	140	13.1
Locator	Locator	69-0936	6.99	123	25	58.00	0.4	9	382	1.81	NLF	2.80	54.1	15.9	1489	8.2
Loiten	Loiten	69-0872	7.05	150	25	28.90	0.3	8	353	1.45	NLF	4.25	39.0	14.9	242	9.1
Long (Itasca)	Long_I	31-0570	8.08	2294	202	10.14	2.1	13	539	2.16	NLF	5.01	54.5	22.9	165	5.4
Long (Kand)	Long_K	34-0066	8.46	3407	348	8.82	9.2	19	563	5.33	NCHF	3.71	129.8	13.4	363	5.4
Loon	Loon_I	31-0571	8.55	2468	219	9.28	2.8	11	563	3.79	NLF	3.70	92.9	21.0	364	6.3
Marcott	Marcott	19-0042	7.76	2393	345	10.33	36.0	19	610	4.53	Metro	3.96	7.5	101.1	251	2.0
McCarrons	McCarrns	62-0054	8.60	1591	395	18.95	74.7	48	1117	13.05	Metro	2.13	30.1	17.4	412	7.6
Ninemile	Ninemile	38-0033	7.39	356	44	16.88	0.8	17	518	2.09	NLF	2.76	120.3	9.1	209	2.4
Nipisiquit	Nipisiqt	38-0232	7.40	486	52	23.18	0.3	16	495	3.45	NLF	2.90	23.7	5.5	298	4.3
Owasso	Owasso	62-0056	8.15	2030	314	15.00	81.0	40	1108	12.24	Metro	2.74	150.9	12.2	423	3.4

Table 5, cont.

Lake	Code	MN DNR ID	pH	ANC	Cond	Color	Cl	TP	TN	Chla	Eco-region	SD	lake area	Z max	Wshed area	Z mean
Richardson	Richrdsn	47-0088	8.29	2715	349	17.89	17.4	98	1500	26.80	NCHF	1.89	48.3	14.3	1168	5.9
Sagatagan	Sagatgn	73-0092	8.45	1741	157	6.94	3.7	27	1048	3.28	NCHF	4.02	88.7	14.3	252	3.0
Schultz	Schultz	19-0075	7.80	1690	249	17.50	32.0	26	655	2.74	Metro	3.39	5.3	4.9	69	2.4
Shoepack	Shoepack	69-0870	6.59	100	21	116.75	0.2	19	593	6.14	NLF	1.54	155.4	7.3	1768	4.3
Snells	Snells	31-0569	8.18	2507	230	17.94	6.3	24	765	4.49	NLF	3.03	35.8	15.2	288	6.0
Square	Square	82-0046	8.70	2430	228	4.00	5.6	12	351	1.49	Metro	6.78	81.9	20.7	226	9.1
Stahl	Stahl	43-0104	8.39	3107	309	19.87	11.6	46	1332	18.65	NCHF	0.99	54.6	10.7	630	4.8
Sweeney	Sweeney	27-0035-01	8.38	4200	883	18.00	183.0	46	647	20.61	Metro	1.70	28.3	7.6	1011	3.7
Tanners	Tanners	82-0115	8.90	2370	505	26.00	99.0	56	1131	10.80	Metro	2.85	30.2	13.7	669	7.0
Tettegouche	Tettgche	38-0231	7.32	303	38	32.93	0.4	17	435	2.96	NLF	2.53	26.7	4.6	103	1.3
Tooth	Tooth	69-0756	6.84	189	30	38.50	0.4	12	445	2.87	NLF	3.93	23.6	13.1	151	6.0
Turtle	Turtle	62-0061	8.26	2320	279	7.50	22.0	27	876	6.54	Metro	2.31	133.3	8.8	180	3.7
Twin	Twin	27-0035-02	8.55	2927	604	13.67	100.0	22	613	2.13	Metro	3.76	8.7	17.1	33	9.4
Wilson	Wilson	38-0047	7.45	342	43	13.66	0.3	13	249	3.05	NLF	3.98	257.1	14.9	719	5.9
Windy	Windy	38-0068	6.94	148	27	98.20	0.3	12	461	1.85	NLF	2.01	184.6	11.9	1705	7.0
Wolf	Wolf	38-0242	7.76	610	70	17.70	1.9	14	385	2.14	NLF	4.10	13.1	7.3	68	3.7
Bingham	Bingham	17-0007	8.46	3600	457	14.00	23.0	217	2144	11.07	WCP	2.03	106.0	3.0	440	2.1
Cottonwood(CT)	Ctnd_CT	17-0022	8.44	3000	466	14.00	20.6	84	1434	33.52	WCP	0.45	61.5	2.7	1140	1.5
Talcott	Talcott	17-0060	8.78	3320	751	24.00	25.4	364	2856	163.46	WCP	0.30	375.6	1.8	134198	1.2
Loon	Loon_J	32-0020	8.42	4400	518	18.00	25.0	664	2080	19.93	WCP	0.50	293.4	2.1	7772	1.2
Clear	Clear	32-0022	8.40	4200	536	16.00	36.8	110	2220	28.38	WCP	0.73	182.5	3.0	466	1.8
Dead Coon	DeadCoon	41-0021	8.75	3480	717	22.00	13.8	176	2394	52.00	NGP	0.90	233.1	2.1	4922	1.5
Benton	Benton	41-0043	8.61	3333	525	21.11	13.1	137	1804	33.06	NGP	0.57	1046.9	2.7	10026	2.1
Shaokatan	Shaoktn	41-0089	8.66	3225	613	20.00	8.0	124	2378	55.10	NGP	1.12	402.7	3.7	3601	2.4
East Twin	ETwin	42-0070	8.88	5933	722	16.67	16.0	104	2283	37.57	NGP	0.95	113.3	6.7	466	3.0
West Twin	WTwin	42-0074	9.08	2900	615	13.75	23.3	46	1330	9.35	NGP	2.10	95.9	3.0	466	1.8
School Grove	SchlGrv	42-0002	8.70	5240	1099	20.00	21.4	127	2352	62.42	NGP	0.48	140.8	3.4	803	2.4
Cottonwood(LY)	Ctnd_LY	42-0014	8.78	3280	1481	22.00	23.6	141	2732	96.18	NGP	0.65	130.7	2.4	5570	1.8
Yankton	Yankton	42-0047	8.46	3240	785	18.00	24.6	137	2080	50.66	NGP	0.47	154.6	2.1	389	1.8
Rock	Rock	42-0052	8.43	3480	740	14.00	16.0	140	1878	27.97	NGP	0.63	170.8	2.1	1114	1.5
Goose	Goose	42-0093	8.44	3760	805	18.00	12.0	150	2298	23.27	NGP	0.60	56.3	2.4	389	2.1
Big Twin	BTwin	46-0133	8.59	4267	514	20.00	32.0	141	2907	52.63	WCP	0.35	180.1	3.0	466	2.4
Lime	Lime	51-0024	8.82	2580	653	23.33	24.7	227	3707	223.35	WCP	0.28	136.8	2.1	15933	1.5
Bloody	Bloody	51-0040	8.53	3160	652	13.00	14.8	89	1678	42.32	WCP	0.54	108.1	3.4	259	1.5
Sarah	Sarah	51-0063	8.42	2840	638	9.00	14.4	102	1640	36.03	NGP	0.54	482.8	1.5	4378	1.2
Currant	Currant	51-0082	8.72	3840	711	20.00	19.8	133	2486	74.74	NGP	0.36	215.7	2.4	648	1.5
East Graham	EGraham	53-0020	8.44	3080	668	22.00	23.8	214	2328	73.42	WCP	0.28	211.7	2.4	9171	1.8
West Graham	WGraham	53-0021	8.75	2840	664	16.00	21.4	110	1720	55.66	WCP	0.44	212.9	2.4	8083	1.8
Curtis (Houst)	Curtis_H	87-0016	8.75	4080	890	20.00	24.4	191	3162	143.80	WCP	0.23	145.7	1.8	1995	1.5
Wood	Wood	87-0030	8.64	3400	893	18.00	21.8	138	1914	39.58	WCP	0.37	185.8	3.0	2332	1.5

Table 6. Diatom taxa used in development of WA_{inv} logTP transfer function, number of occurences and maximum relative abundance in 79 Minnesota lake training set, total phosphorus optima (μg/L), Great Lakes Environmental Indicators diatom species codes, and DIATCODE species labels used in Ramstack *et al*. (2003).

Taxon	no. lakes	maximum percent abundance	TP optimum (μg/L)	GLEI code	DIATCODE
Achnanthes conspicua	9	2.3	17.6	ACHCONSP	AC023A
Achnanthes grana	3	1.6	29.8	ACEGRANA	AC158A
Achnanthes lanceolata	10	1.7	30.7	PLALANCE	AC001A
Achnanthes lanceolata ssp. frequentissima	13	1.4	21.8	PLAFREQU	AC001R
Achnanthes lanceolata v. rostrata	8	2.2	28.9	PLAROSTR	AC001B
Achnanthes linearis	4	2.6	17.5	ROSLINEA	AC002A
Achnanthes minutissima	47	30.5	17.2	ACHMINUT	AC013A
Amphora inariensis	14	4.5	114.8	AMPINARI	AM013A
Amphora libyca	35	20.7	118.4	AMPLIBYC	AM011A
Amphora ovalis	5	2.8	133.7	AMPOVALI	AM001A
Amphora pediculus	18	2.0	41.8	AMPPEDIC	AM012A
Anomoeoneis sphaerophora f. costata	2	2.4	113.3	ANOSPHAE	AN009D
Anomoeoneis vitrea	10	4.5	11.1	BRAVITRE	AN004A
Asterionella formosa	55	52.1	20.0	ASTFORMO	AS001A
Aulacoseira alpigena	7	3.0	14.5	AULALPIG	AU031A
Aulacoseira ambigua	67	45.6	54.4	AULAMBIG	AU002A
Aulacoseira crenulata	14	16.5	129.0	AULCRENU	AU001D
Aulacoseira distans	12	17.1	13.8	AULDISTA	AU005A
Aulacoseira granulata	47	74.4	118.1	AULGRANU	AU003A
Aulacoseira italica	5	1.3	45.7	AULITALI	AU001A
Aulacoseira lirata v. biseriata	4	5.7	15.9	AULLIRBI	AU004C
Aulacoseira pfaffiana	5	5.3	11.9	AULPFAFF	AU032A
Aulacoseira subarctica	22	10.4	29.1	AULSUBAR	AU020A
Caloneis schumanniana	5	1.3	137.9	CALSCHUM	CA010A
Cocconeis neodiminuta	5	1.3	46.3	COCNEODI	CO066A
Cocconeis neothumensis	4	1.7	17.5	COCNEOTH	CO067A
Cocconeis pediculus	10	1.3	91.9	COCPEDIC	CO005A
Cocconeis placentula	31	9.5	53.3	COCPLACE	CO001A
Cocconeis placentula v. euglypta	28	4.2	36.4	COCPLAEU	CO001B
Cocconeis placentula v. lineata	18	9.0	67.5	COCPLALI	CO001C
Cyclostephanos dubius	13	2.7	105.8	CSPDUBIU	CC001A
Cyclostephanos invisitatus	6	4.7	70.4	CSPINVIS	CC002A
Cyclostephanos tholiformis	17	3.3	109.1	CSPTHOLI	CC003A
Cyclotella bodanica v. lemanica	38	40.7	13.8	CYCBODLE	CY058A
Cyclotella comensis	4	36.4	12.5	CYCCOMEN	CY010A
Cyclotella comta/radiosa	3	1.9	100.3	CYCCOMRA	
Cyclotella krammeri	5	2.1	15.1	CYCKRAMM	CY054A
Cyclotella meneghiniana	27	18.2	125.6	CYCMENEG	CY003A
Cyclotella michiganiana	30	10.4	15.6	CYCMICHI	CY005A
Cyclotella ocellata	13	50.5	28.4	CYCOCELL	CY009A

Table 6, cont.

Cyclotella pseudostelligera	29	58.9	11.0	CYCPSEUD	CY002A
Cyclotella rossii	4	9.5	116.8	CYCROSSI	CY052A
Cyclotella stelligera	17	18.1	12.6	CYCSTELL	CY004A
Cymatopleura elliptica	10	1.2	126.2	CYTELLIP	CL002A
Cymbella affinis	2	1.3	14.5	CYMAFFIN	CM022A
Cymbella cesatii	4	1.2	11.2	CYMCESAT	CM015A
Cymbella cistula	11	1.4	26.9	CYMCISTU	CM006A
Cymbella descripta	4	1.2	12.3	CYMDESCR	CM052A
Cymbella muelleri	5	1.0	148.4	ENCMUELL	EY012A
Cymbella muelleri f. ventricosa	4	0.9	122.1	ENCMUEVE	CM024B
Cymbella silesiaca	21	2.9	19.8	ENCSILEA	CM103A
Cymbella triangulum	13	6.9	131.0	ENCTRIAL	CM111A
Cymbella turgidula	2	2.9	14.0	CYMTURGI	CM110A
Diatoma elongatum	3	2.2	22.1	DIATENEL	DT004B
Epithemia adnata	8	2.2	91.8	EPIADNAT	EP007A
Epithemia adnata v. proboscidea	6	1.0	123.6	EPIADNPR	EP007F
Epithemia turgida	4	1.2	103.0	EPITURGI	EP004A
Eunotia bilunaris	9	1.3	20.6	EUNBILUN	EU070A
Eunotia zasumenensis	3	27.9	17.7	EUNZASUM	EU059A
Fragilaria brevistriata	51	55.9	24.2	PRABREVI	FR006A
Fragilaria brevistriata/pinnata	5	1.0	24.0	FR069A	FR069A
Fragilaria capucina	13	10.7	51.5	FRACAPUC	FR009A
Fragilaria capucina v. gracilis	10	11.9	27.8	FRACAPGR	FR009H
Fragilaria capucina v. mesolepta	33	45.1	56.2	FRACAPME	FR009B
Fragilaria capucina v. rumpens	8	14.5	38.1	SYNRUMPE	FR009G
Fragilaria construens	39	25.5	28.2	SRACONST	FR002A
Fragilaria construens v. binodis	7	5.5	17.0	SRACONBI	FR002B
Fragilaria construens v. venter	47	31.4	22.2	SRACONVE	FR002C
Fragilaria construens var. 2	1	1.0	35.7	SRACOV2MN	
Fragilaria crotonensis	43	56.7	21.9	FRACROTO	FR008A
Fragilaria exigua	8	4.7	17.5	FRAEXIGU	FR066A
Fragilaria pinnata	36	22.5	21.9	SLLPINNA	FR001A
Fragilaria tenera (FragPISCES1)	5	4.6	14.8	FRETENER	FR060A
Fragilaria vaucheriae	36	5.0	78.6	FRAVAUCH	FR062A
Gomphonema affine v. insigne	15	13.4	146.8	GOMAFFIN	GO020B
Gomphonema angustatum	9	5.1	152.5	GOMANGUS	GO003A
Gomphonema angustum	4	1.5	61.8	GOMANGUT	GO073A
Gomphonema dichotomum	2	4.5	11.9	GOMDICHO	
Gomphonema pumilum	10	1.5	39.5	GOMPUMIL	GO080A
Gomphonema subclavatum	7	1.4	100.1	GOMSUBCL	GO030A
Hantzschia amphioxys	8	2.8	121.2	HANAMPHI	HA001A
Hippodonta capitata	11	1.5	168.1	HIPCAPIT	NA066A
Martyana martyi	2	2.8	7.6	MARMARTY	FR065A
Navicula accomoda	6	3.5	13.8	CRAACCOM	NA096A
Navicula bacilliformis	3	2.1	14.6	SELBACIL	NA102A
Navicula cincta	9	5.2	44.8	NAVCINCT	NA021A

Table 6, cont.

Navicula crucicula	4	2.4	36.1	NAVCRUCI	NA067A
Navicula cryptocephala	24	3.0	23.9	NAVCRYPT	NA007A
Navicula cuspidata	21	6.6	113.5	CRACUSPI	NA056A
Navicula decussis	8	1.3	53.7	PLQDECUS	NA317A
Navicula diluviana	2	3.1	40.5	NAVDILUV	CM034A
Navicula erifuga	10	2.3	145.8	NAVERIFU	NA173A
Navicula graciloides	3	1.1	18.1	NAVGRACH	NA055A
Navicula halophila	17	2.3	12.6	CRAHALOP	NA022A
Navicula heufleri	4	1.3	157.7	NAVHEUFL	NA094A
Navicula mutica	6	1.0	158.2	LUTMUTIC	LU001A
Navicula pseudoscutiformis	4	1.2	16.0	CAVPSEUD	NA013A
Navicula pseudoventralis	5	2.9	16.5	NAVPSEUV	NA590A
Navicula pupula	27	11.8	18.3	SELPUPUL	NA014A
Navicula radiosa	11	1.1	18.5	NAVRADIO	NA003A
Navicula recens	22	2.2	24.0	NAVRECEN	NA762A
Navicula reinhardtii	9	1.2	122.6	NAVREINH	NA026A
Navicula seminulum	8	3.4	23.1	NAVSEMIN	NA005A
Navicula subalpina	5	1.7	26.2	NAVSUBAL	NA767A
Navicula tenella	19	2.9	17.2	NAVCRYTE	NA751A
Navicula trivialis	10	2.2	132.4	NAVTRIVI	NA063A
Nitzschia acicularioides	4	2.1	99.3	NITACICI	NI057A
Nitzschia amphibia	23	2.7	50.8	NITAMPHI	NI014A
Nitzschia archibaldii	3	1.1	23.8	NITARCHI	NI065A
Nitzschia bacilliformis	4	3.4	73.5	NITBACIL	NI210A
Nitzschia fonticola	15	4.2	40.0	NITFONTI	NI002A
Nitzschia gracilis	22	4.2	27.1	NITGRACI	NI017A
Nitzschia hungarica	8	1.5	148.8	TRYHUNGA	TF015A
Nitzschia kuetzingii	7	2.1	33.1	NITKUETZ	NI152A
Nitzschia lacuum	7	1.9	15.0	NITLACUU	NI198A
Nitzschia linearis v. subtilis	13	2.1	141.8	NITLINSU	NI031C
Nitzschia linearis v. tenuis	4	1.6	159.3	NITLINTE	NI031B
Nitzschia palea	4	1.3	196.9	NITPALEA	NI009A
Nitzschia perminuta/frustulum	15	6.1	116.5	NITPERFR	
Nitzschia vermicularis	9	1.0	114.1	NITVERMI	NI049A
Pinnularia brauniana	4	2.6	15.2	PINBRAUN	PI170A
Pinnularia microstauron v. brebissonii	7	1.4	127.0	PINBREBI	PI048A
Pinnularia viridis	16	3.1	126.6	PINVIRID	PI007A
Rhoicosphenia curvata	15	2.3	129.4	RHOCURVA	RC002A
Rhopalodia gibba	9	1.3	74.7	RHPGIBBA	RH001A
Stauroneis anceps	7	2.5	18.5	STAANCEP	SA001A
Stephanodiscus hantzschii	31	9.7	59.1	SUSHANTZ	ST001A
Stephanodiscus medius	15	2.2	27.7	SUSMEDIU	ST014A
Stephanodiscus minutulus	43	45.7	49.8	SUSMINUT	ST021A
Stephanodiscus niagarae	52	31.8	122.4	SUSNIAGA	ST006A
Stephanodiscus oregonicus	1	9.7	18.5	SUSOREGO	ST027A
Stephanodiscus parvus	48	62.0	46.0	SUSPARVU	ST010A

Table 6, cont.

Surirella ovalis	17	5.9	141.8	SUROVALI	SU003A
Synedra acus	20	2.0	90.0	SYNACUS	SY003A
Synedra cyclopum	4	1.8	19.2	SYNCYCLO	SY081A
Synedra ulna	24	3.8	53.6	SYNULNA	SY001A
Tabellaria fenestrata	9	2.9	14.2	TABFENES	TA002A
Tabellaria flocculosa III	22	46.4	10.8	TABFLOC3	TA001A
Tabellaria flocculosa IV	6	1.3	17.7	TABFLOC4	TA001E
Tabellaria quadriseptata	8	12.6	11.0	TABQUADR	TA005A
Tryblionella angustata	10	1.0	112.8	TRYANGUS	NI020A

Table 7. Diatom-inferred total phosphorus (DI-TP) reconstructions from training set surface sediment samples (surf) and sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2000-2003 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2002 mean epilimnetic TP and range of observed TP values are listed for all six lakes. The dissimilariy coefficient (DC) is calculated as the squared chi-squared distance between a fossil sample and its nearest modern analog among the 76 lakes in the logTP transfer function. A good analogue is defined with a DC<0.6284, the fifth percentile of distance distributions among the modern samples. Appended at the end of the table are recalculations of TP using the new 79 lake training set from the five southern Minnesota lakes cored by Ramstack *et al*. (2003).

Name	DI-TP (ppb)	2002 observed mean TP (ppb)	2002 observed TP range (ppb)	modern analogue?	DC
BTwin (surf)	114	141	126-154	—	—
BTwin2	131	—	—	analogue	0.3997
BTwin80	42	—	—	no analogue	0.8166
BTwin90	72	—	—	analogue	0.3804
Bloody (surf)	181	89	67-121	—	—
Bloody2	156	—	—	analogue	0.3854
*Bloody52	127	—	—	analogue	0.447
Bloody62	60	—	—	no analogue	0.719
Bloody72	77	—	—	no analogue	0.9084
Clear (surf)	67	110	69-137	—	—
Clear2	106	—	—	no analogue	0.7276
Clear58	34	—	—	analogue	0.567
Clear68	27	—	—	no analogue	0.7383
Ctnd_CT (surf)	122	83	63-133	—	—
Ctnd_CT2	113	—	—	analogue	0.2321
Ctnd_CT72	94	—	—	no analogue	0.6782
Ctnd_CT82	98	—	—	no analogue	0.6671
ETwin (surf)	186	104	84-121	—	—
ETwin2	137	—	—	analogue	0.6134
ETwin68	110	—	—	no analogue	0.851
ETwin78	86	—	—	no analogue	0.8948
Shaoktn (surf)	105	124	75-159	—	—
Shaoktn2	108	—	—	no analogue	0.7152
Shaoktn56	48	—	—	analogue	0.4721
Shaoktn66	52	—	—	analogue	0.3711

*Bloody52 was determined to represent sediments deposited after European settlement.

Table 7, cont. Diatom-inferred total phosphorus (DI-TP) reconstructions from training set surface sediment samples (surf) and sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2000-2003 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2002 mean epilimnetic TP and range of observed TP values are listed for all six lakes. The dissimilariy coefficient (DC) is calculated as the squared chi-squared distance between a fossil sample and its nearest modern analog among the 76 lakes in the logTP transfer function. A good analogue is defined with a DC<0.6284, the fifth percentile of distance distributions among the modern samples. Appended at the end of the table are recalculations of TP using the new 79 lake training set from the five southern Minnesota lakes cored by Ramstack *et al*. (2003).

Lake name (Ramstack 1999; used in 55 MN lakes)**	**DI-TP (ppb)**	**1993-98 observed mean TP (ppb)**	**DI-TP from Ramstack (1999)**	**modern analogue?**	**DC**
Bass1990s	52	81	64	—	—
Bass1800	55	–	46	analogue	0.6031
Bass1750	90	–	65	analogue	0.5434
Beaver1990s	35	30	41	—	—
Beaver1800	49	–	37	no analogue	0.9344
Beaver1750	58	–	39	analogue	0.3953
Duck1990s	41	65	37	—	—
Duck1800	29	–	24	no analogue	0.7851
Duck1750	53	–	39	no analogue	0.7237
Fish_J1990s	48	38	55	—	—
Fish_J1800	87	–	61	analogue	0.6313
Fish_J1750	83	–	67	analogue	0.5954
George_B1990s***	30	130	37	analogue	0.6037
George_B1800	76	–	58	analogue	0.4089
George_B1750	41	–	32	no analogue	0.9044

*Bloody52 was determined to represent sediments deposited after European settlement.

**The Ramstack 1990s DI-TP were derived from the same samples as used to create the 55 MN lakes transfer function.

***George Lake in Blue Earth County was identified as an outlier and removed in the development of the 79 lake transfer function.

FIGURES

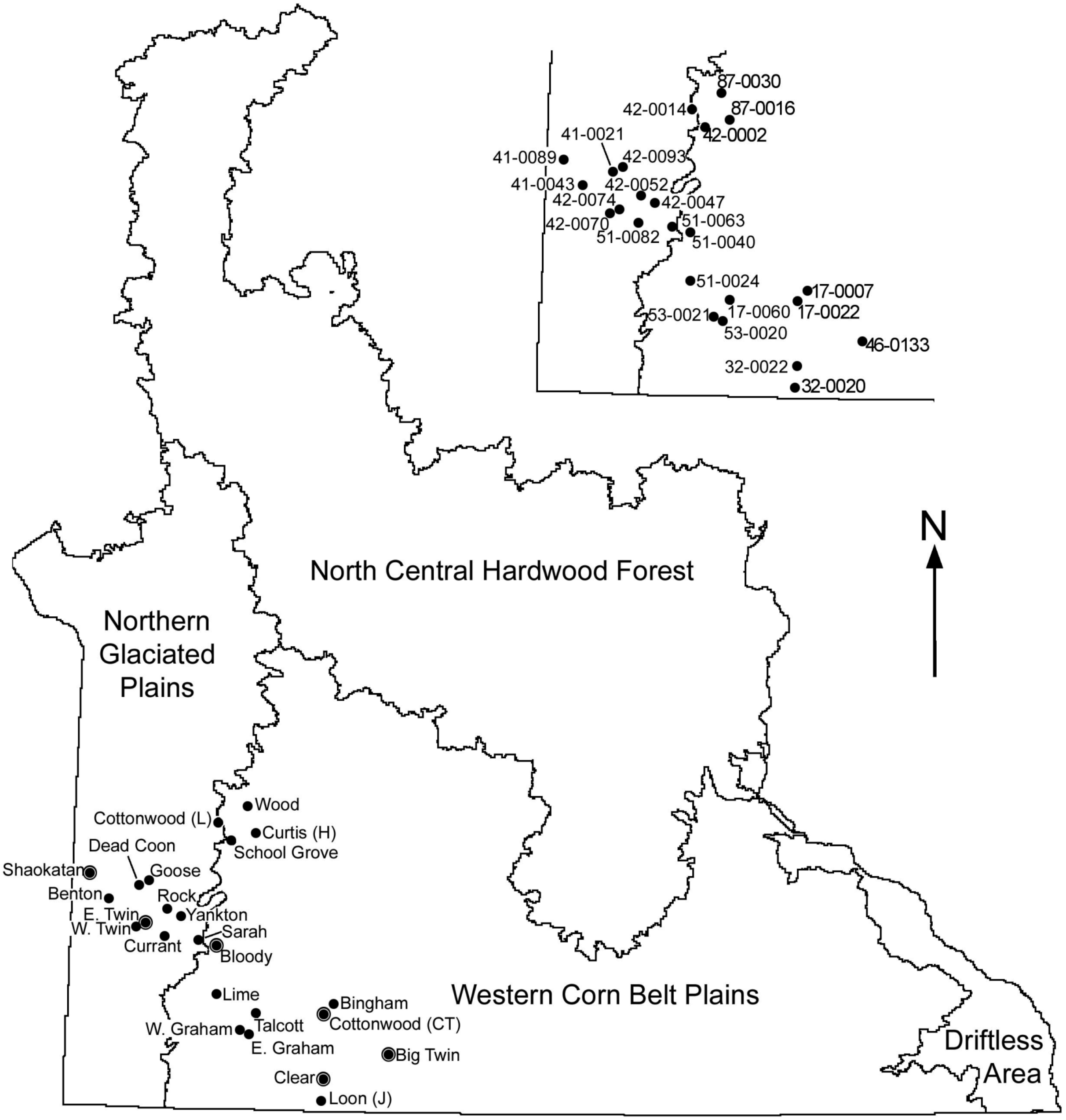


Figure. 1. Location, USEPA ecoregions, and Minnesota Department of Natural Resources Lake ID for 24 lakes sampled in southwest Minnesota. Lakes cored in 2003 indicated with double circles.

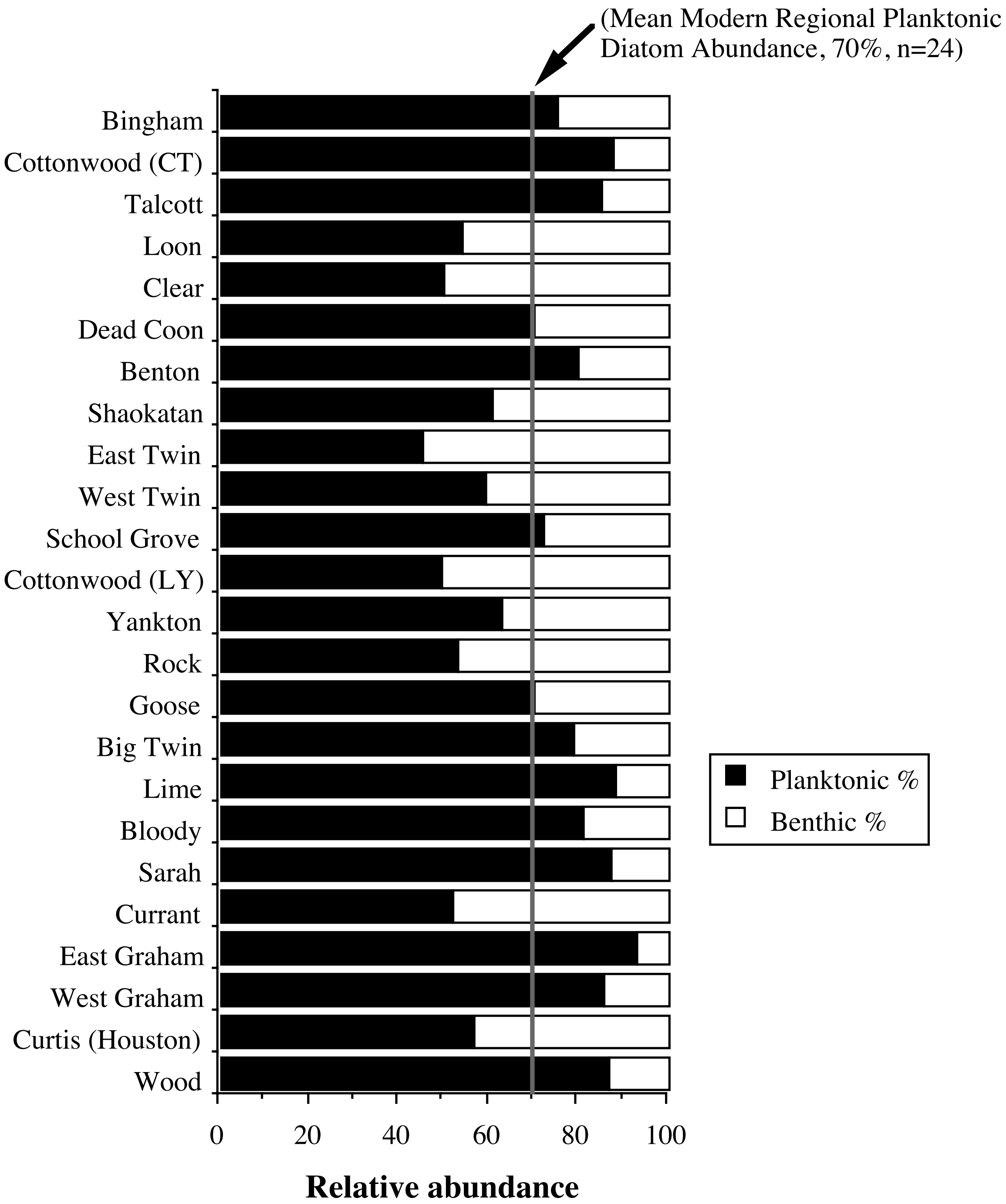


Figure 2. Relative abundance of planktonic and benthic diatoms in surface sediment samples from 24 southwest Minnesota lakes. Mean abundance of planktonic diatom in surface sediments among all lakes is indicated by gray line.

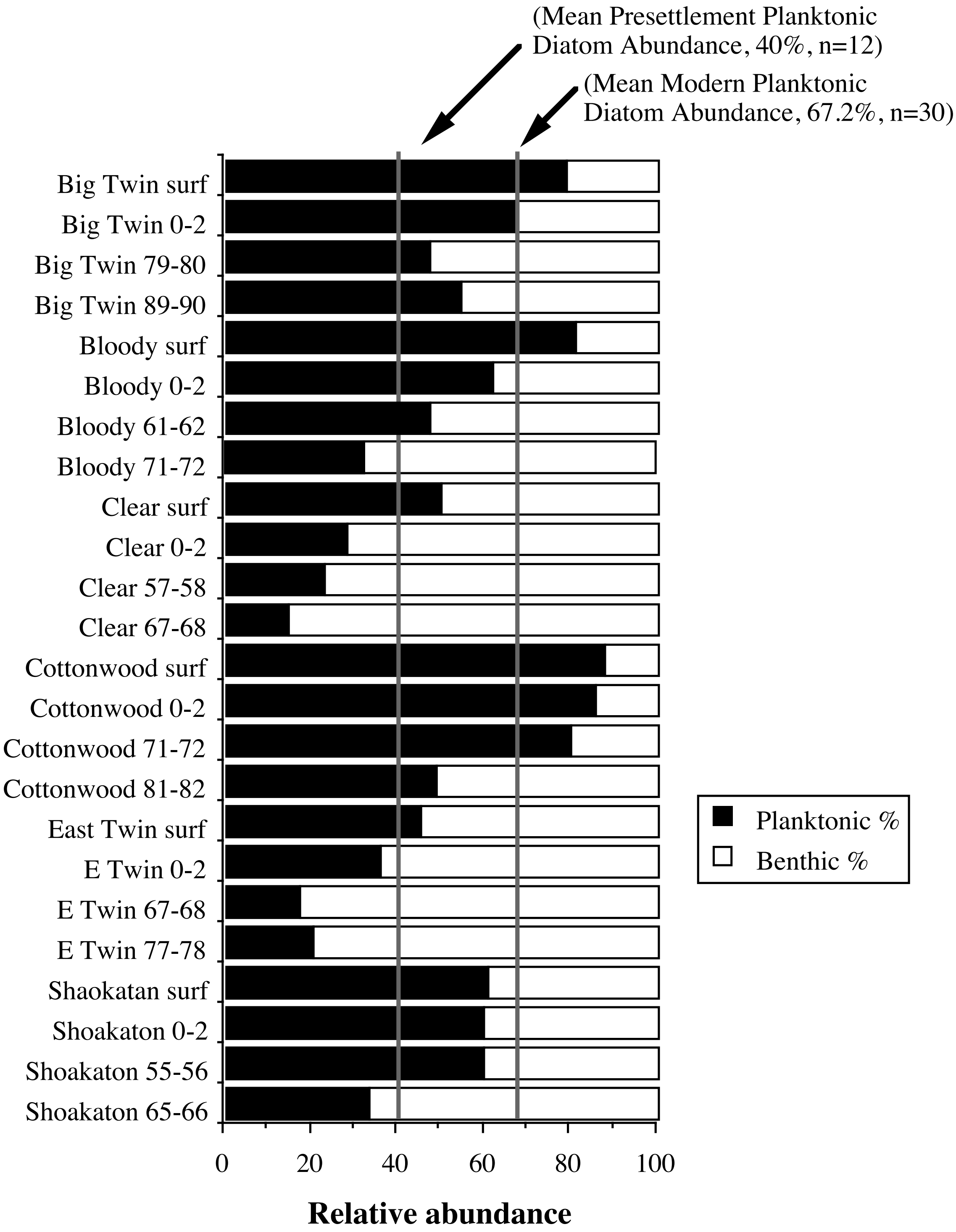
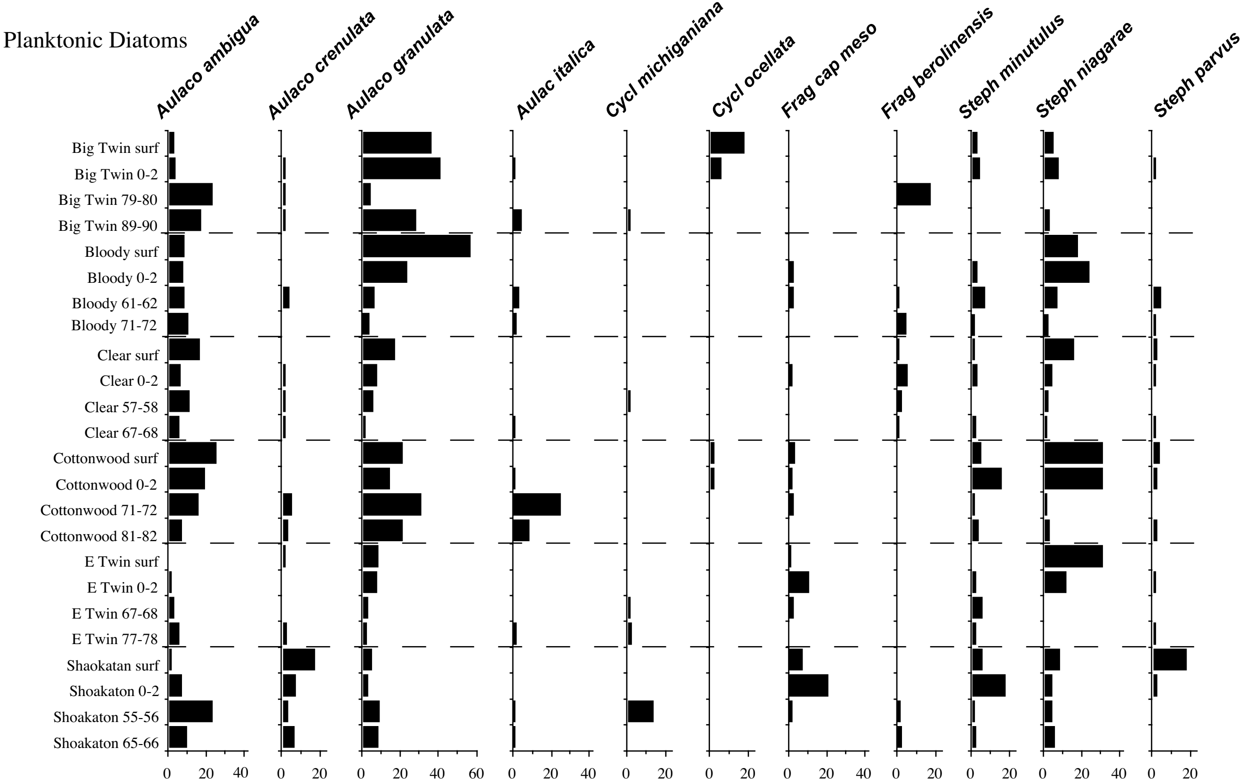


Figure 3. Downcore relative abundance of planktonic diatoms and benthic diatoms from six sediment cores (excluding Bloody52) and six surface sediment samples from southwest Minnesota lakes. Mean abundance of planktonic diatoms in presettlement and modern times is indicated by gray lines.

Southwest Minnesota Lakes, sediment cores



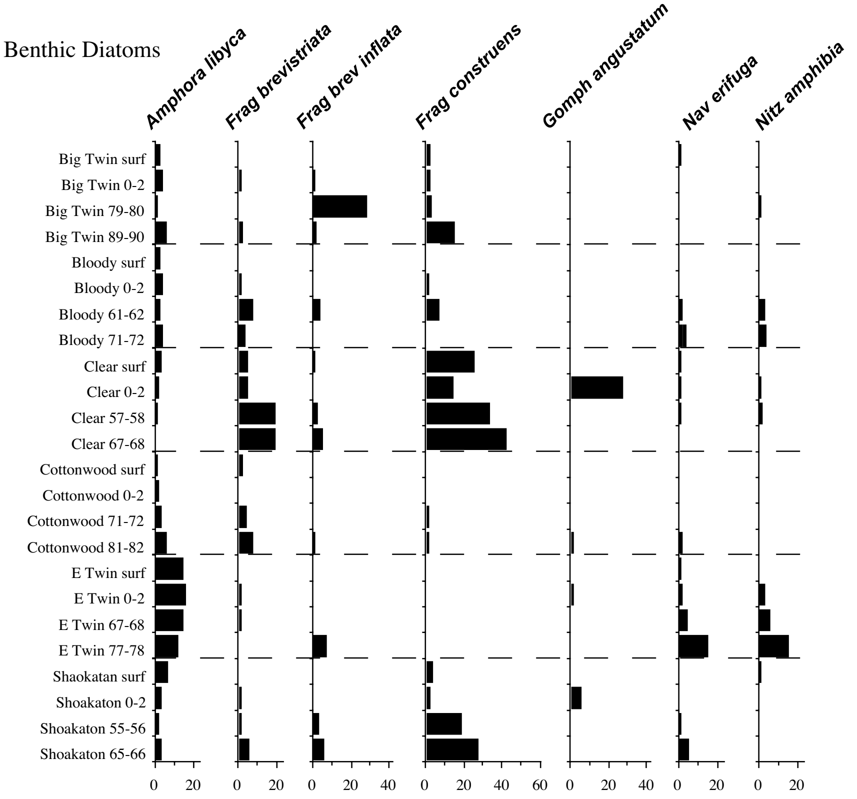


Figure 4. Downcore distribution of diatom taxa found at >10% relative abundance in sediment cores recovered from southwest Minnesota lakes. Numbers on ordinate refer to depth (cm) below sediment-water interface

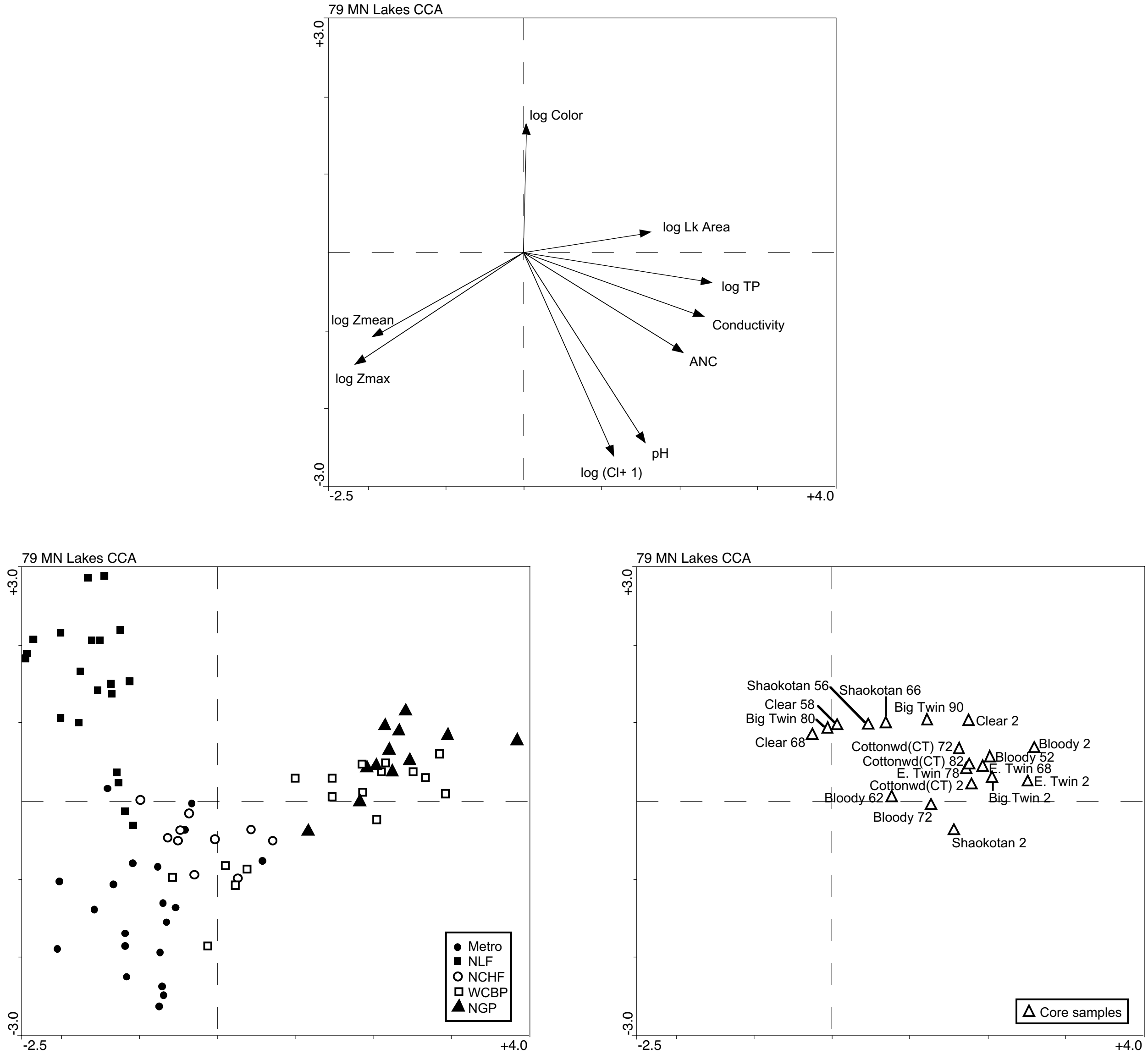


Figure 5. Ordination biplots of axis 1 (horizontal) and axis 2 (vertical) from canonical correspondance analysis of 79 Minnesota lakes diatom training set. Top panel shows direction and vector lengths of nine environmental variable identified by forward selection as independently explaining significant variation in the species data. Lower left panel plots 79 Minnesota lakes with symbols corresponding to USEPA ecoregions. Minneapolis-St. Paul metro area lakes are separately labelled. Lower right plot shows 19 samples from six SW Minnesota sediment cores plotted in CCA ordination space.

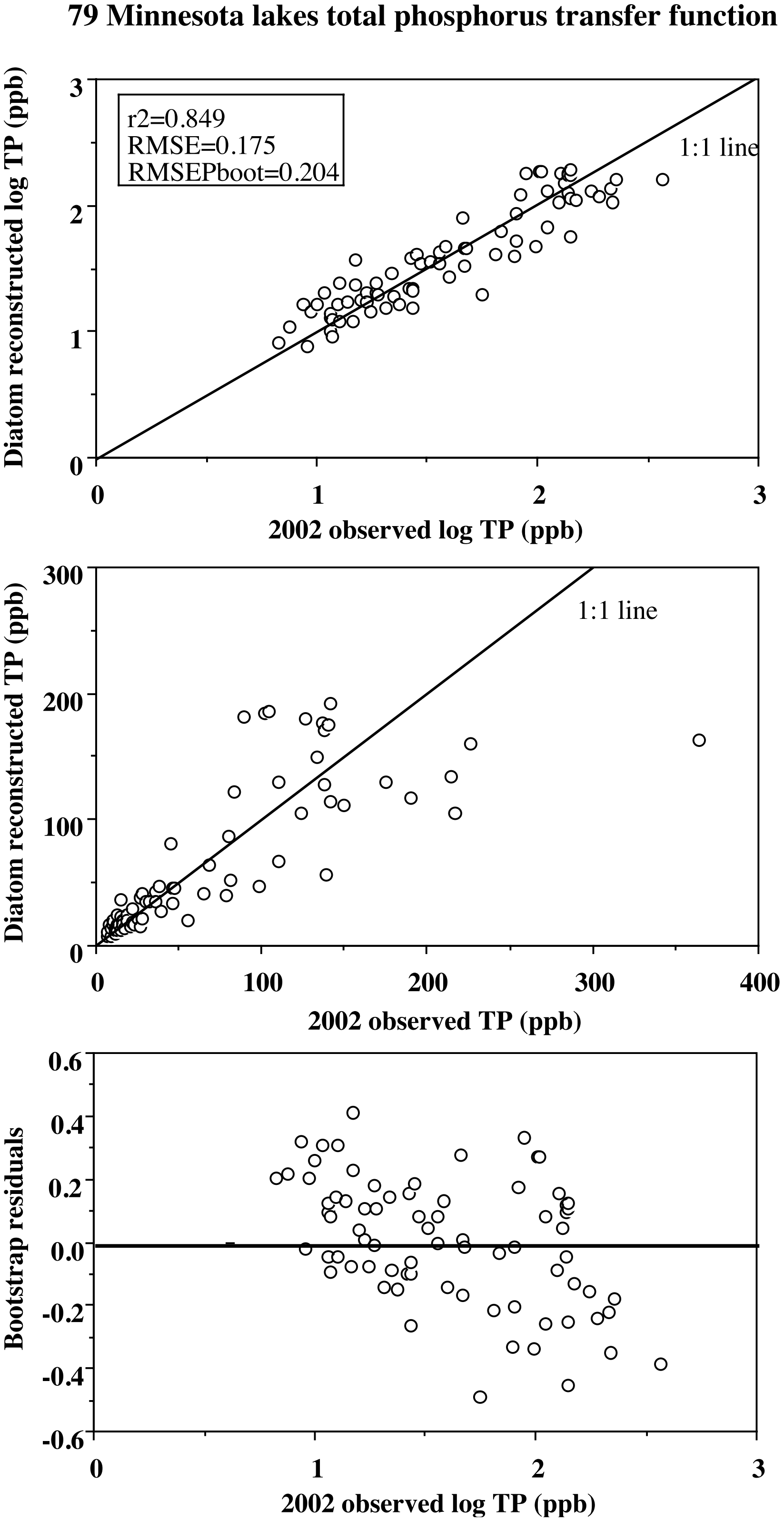


Figure 6. Summary performance of weighted average log TP transfer function. Top two panels are 2002 observed vs diatom reconstructed log TP or back-calculated TP. Bottom panel is observed TP vs bootstrap residual estimates.

APPENDIX 1-CORE SCANS, MAGNETICS LOGGING, GAMMA ANALYSIS OF UNSUPPORTED 210-LEAD, AND DIATOM SAMPLING