



Biomonitoring Using Diatoms and Paleolimnology in the Western Great Lakes National Parks

Natural Resource Technical Report NPS/GLKN/NRTR—2012/644



ON THE COVER

Surface sediment diatoms collected in 2010 from Ryan Lake in Voyageurs National Park include *Pinnularia*, *Aulacoseira*, *Staurosira*, and *Urosolenia* species. Photo by Mark Edlund, St. Croix Watershed Research Station.

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Mark B. Edlund¹, Joy Ramstack Hobbs, and Daniel R. Engstrom

St. Croix Watershed Research Station
Science Museum of Minnesota
16910 152nd St North
Marine on St. Croix, Minnesota 55047
¹mbedlund@smm.org

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Page 9, “Diatom-inferred Water Quality Measures”

1. Tables 4a and 4b are referenced in this section, but the tables were not included in the report. They are shown below.
2. Sentence 2 of paragraph 1 reads (bold text not in original)

*Estimates of diatom-inferred TP (DI-TP) suggested most of the VOYA lakes are oligotrophic to mesotrophic with DI-TP ranging from 5.5 µg/L TP **in Jorgens Lake** to 15.6 µg/L TP in Ryan Lake.*

Is corrected to read as follows

*Estimates of diatom-inferred TP (DI-TP) suggested most of the VOYA lakes are oligotrophic to mesotrophic with DI-TP ranging from 5.5 µg/L **in Little Trout Lake** to 15.6 µg/L TP in Ryan Lake.*

See Table 4a below.

3. Paragraph 3 in this section discusses estimates of DI-pH. Table 4c displays these data, but it was not referenced or included in the report. Table 4c is shown below.

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Table 4a. Diatom inferred estimates of TP based on transfer functions developed for the GLKN lakes by Edlund et al. (2011). Model estimates of TP are calculated in log units but have been back-transformed to $\mu\text{g/L}$ TP. Model error estimates are given for the low and high range of DI-TP based on model RMSEP (Edlund et al. 2011). The range of mean annual measures of TP is also given for each lake based on monitoring data from 2006–2010 (Elias and VanderMeulen 2008, Elias 2009, Elias and Damstra 2011).

Lake	Total phosphorus ($\mu\text{g/l}$ TP)				
	mean annual TP		diatom-inferred TP		
	min	max	DI-TP	low range	high range
Agnes	23	23	14.1	9.1	21.7
Brown	7	14	9.2	6.0	14.2
Cruiser	3	5	6.4	4.2	9.9
Ek	16	24	9.7	6.3	15.0
Jorgens	11	11	11.6	7.5	17.9
Little Trout	4	5	5.5	3.6	8.5
Locator 0-1 cm	7	13	7.5	4.9	11.6
Locator 0-2 cm	7	13	7.3	4.8	11.3
Mukooda	8	8	9.7	6.3	14.9
O'Leary	9	9	12.8	8.3	19.7
Oslo	8	8	8.8	5.7	13.6
Peary	15	24	11.2	7.2	17.2
Quarterline	16	16	14.2	9.2	21.9
Ryan	9	11	15.6	10.1	24.1
Shoepack 0-1 cm	17	29	13.9	9.0	21.5
Shoepack 0-2 cm	17	29	13.9	9.0	21.5
Tooth	9	9	7.5	4.8	11.5
War Club	8	8	8.1	5.3	12.5

Addendum—Correction to Edlund, M. B., J. Ramstack Hobbs, and D. R. Engstrom. 2012. Biomonitoring using diatoms and paleolimnology in the western Great Lakes national parks. Natural Resource Technical Report NPS/GLKN/NRTR—2012/644.

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Table 4b. Diatom inferred estimates of EC25 based on transfer functions developed for the GLKN lakes by Edlund et al. (2011). Model estimates of EC25 are calculated in log units but have been back-transformed to $\mu\text{g/L}$ EC25. Model error estimates are given for the low and high range of DI- EC25 based on model RMSEP (Edlund et al. 2011). The range of mean annual measures of EC25 is also given for each lake based on monitoring data from 2006–2010 (Elias and VanderMeulen 2008, Elias 2009, Elias and Damstra 2011).

Lake	EC25 ($\mu\text{S/cm}$)				
	<i>mean annual EC25</i>		<i>diatom-inferred EC25</i>		
	<i>min</i>	<i>max</i>	<i>DI-EC25</i>	<i>low range</i>	<i>high range</i>
Agnes	22	24	22.1	14.7	33.3
Brown	19	23	26.5	17.6	39.9
Cruiser	19	21	31.4	20.8	47.3
Ek	26	33	33.9	22.5	51.1
Jorgens	24	26	49.2	32.7	74.2
Little Trout	34	37	44.8	29.8	67.6
Locator 0-1 cm	24	26	19.1	12.7	28.8
Locator 0-2 cm	24	26	17.2	11.4	25.9
Mukooda	53	57	43.5	28.9	65.6
O'Leary	60	66	53.6	35.6	80.8
Oslo	20	23	20.9	13.9	31.5
Peary	24	31	25.7	17.1	38.8
Quarterline	24	26	34.2	22.7	51.6
Ryan	23	33	63.7	42.2	95.9
Shoepack 0-1 cm	21	27	25.1	16.7	37.8
Shoepack 0-2 cm	21	27	25.5	16.9	38.4
Tooth	29	32	21.3	14.2	32.1
War Club	25	27	21.4	14.2	32.3

Addendum—Correction to Edlund, M. B., J. Ramstack Hobbs, and D. R. Engstrom. 2012. Biomonitoring using diatoms and paleolimnology in the western Great Lakes national parks. Natural Resource Technical Report NPS/GLKN/NRTR—2012/644.

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Table 4c. Diatom inferred estimates of pH based on transfer functions developed for the GLKN lakes by Edlund et al. (2011). Model error estimates are given for the low and high range of DI-pH based on model RMSEP (Edlund et al. 2011). The range of mean annual measures of pH is given for each lake based on monitoring data from 2006-2010 (Elias and VanderMeulen 2008, Elias 2009, Elias and Damstra 2011).

Lake	pH (standard units)				
	<i>mean annual</i>		<i>DI-pH</i>	<i>diatom-inferred pH</i>	
	<i>pH</i>				
	<i>min</i>	<i>max</i>		<i>low range</i>	<i>high range</i>
Agnes	6.3	6.4	6.72	6.32	7.13
Brown	6.8	7.3	6.98	6.58	7.39
Cruiser	7.1	7.7	7.28	6.88	7.68
Ek	7.0	7.6	7.14	6.74	7.54
Jorgens	6.9	7.2	7.34	6.93	7.74
Little Trout	7.7	7.8	7.68	7.28	8.08
Locator 0-1 cm	6.8	7.5	6.80	6.40	7.20
Locator 0-2 cm	6.8	7.5	6.69	6.29	7.09
Mukooda	7.9	8.0	7.42	7.01	7.82
O'Leary	7.7	8.7	7.46	7.06	7.86
Oslo	7.0	7.3	6.82	6.42	7.22
Peary	7.0	7.6	6.90	6.50	7.31
Quarterline	6.4	6.5	6.98	6.57	7.38
Ryan	6.8	7.2	7.34	6.93	7.74
Shoepack 0-1 cm	6.3	7.0	6.85	6.44	7.25
Shoepack 0-2 cm	6.3	7.0	6.85	6.45	7.26
Tooth	6.9	6.9	6.87	6.47	7.27
War Club	6.8	7.12	6.89	6.49	7.30

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Contents

	Page
Figures.....	v
Tables.....	vii
Acronyms Used in This Report.....	ix
Executive Summary	xi
Acknowledgments.....	xiii
Introduction.....	1
Methods.....	3
Water Quality Sampling	3
Surface Sediment Collection	3
Sediment Processing and Diatom Analysis	4
Numerical Analysis	4
Results.....	7
Water Quality (VOYA 2006-2010)	7
Surface Sediment Diatom Assemblages	8
Ecological Change in VOYA Lakes (2006-2010).....	9
Diatom-inferred Water Quality Measures	9
Diatom Community Change	9
Environmental Change in Relation to Cored VOYA Lakes	15
Ecological Change in High Sedimentation Lakes (Locator, Shoepack).....	19
Conclusions.....	21
Literature Cited	23

Figures

	Page
Figure 1. Plot of squared chord distances for long sediment cores and surface repeat samples from GLKN park lakes.	10
Figure 2. The 2010 repeat surface sediment samples from VOYA lakes (Agnes, Brown, Cruiser, Ek, and Jorgens) passively plotted on the CCA of the GLKN diatom calibration set.	12
Figure 3. The 2010 repeat surface sediment samples from VOYA lakes (Little Trout, Locator 0-1 cm, Locator 0-2 cm, Mukooda, and O'Leary) passively plotted on the CCA of the GLKN diatom calibration set.	13
Figure 4. The 2010 repeat surface sediment samples from VOYA lakes (Oslo, Peary, Quarterline, and Ryan) passively plotted on the CCA of the GLKN diatom calibration set.	14
Figure 5. The 2010 repeat surface sediment samples from VOYA lakes (Shoepack 0-1 cm, Shoepack 0-2 cm, Tooth, and War Club) passively plotted on the CCA of the GLKN diatom calibration set.....	15
Figure 6. DCA of downcore diatom assemblages from Cruiser Lake core (VOYA, 1783-2004) including the 2010 repeat surface sample	17
Figure 7. DCA of downcore diatom assemblages from Ek Lake core (VOYA, 1778-2000) including the 2010 repeat surface sample.....	18
Figure 8. DCA of downcore diatom assemblages from Peary Lake core (VOYA, 1786-2001) including the 2010 repeat surface sample	19

Tables

	Page
Table 1. VOYA lakes and date and location of sampling where surface sediments were collected in 2010.	3
Table 2. Summary of mean annual water quality measures from sixteen lakes at Voyageurs National Park, Minnesota.	7
Table 3. Predominant diatoms (>5% relative abundance) in sediment samples collected from lakes at Voyageurs National Park, Minnesota, in 2010.....	8

Acronyms Used in This Report

CCA	Canonical correspondence analysis
DCA	Detrended correspondence analysis
DOC	Dissolved organic carbon
EC25	Specific conductance normalized to 25°C
INDU	Indiana Dunes National Lakeshore
MISS	Mississippi National River and Recreation Area
PIRO	Pictured Rocks National Lakeshore
SACN	St. Croix National Scenic Riverway
SCWRS	St. Croix Watershed Research Station
SLBE	Sleeping Bear Dunes National Lakeshore
TN	Total nitrogen
TP	Total phosphorus
VOYA	Voyageurs National Park
WQ	Water quality

Executive Summary

1) The 2010 diatom biomonitoring activities targeted eight index and eight non-index lakes in Voyageurs National Park (VOYA). Repeat surface sediments were collected from all 16 lakes and their diatom assemblages were analyzed. The GLKN diatom transfer functions were applied to all repeat sediment samples to estimate TP, pH, and EC25. The 2010 repeat diatom samples were compared to surface sediments taken in 2006 to determine floristic change using the squared chord distance. Repeat surface sediment diatom communities from VOYA lakes were passively plotted on the species-environment ordination of the GLKN lakes to determine recent ecological trajectories and explore what environmental factors may be driving changes in modern diatom communities. Repeat samples were also plotted on ordinations of long sediment cores recovered from three VOYA lakes in 2006.

2) Diatoms preserved in the 2010 surface sediment samples were extremely diverse with over 450 diatom taxa recorded. Assemblages were dominated by the planktonic or softwater taxa *Tabellaria flocculosa* IIIp, *Discostella stelligera*, *Asterionella formosa*, *Aulacoseira tenella*, *A. ambigua*, and *Eunotia zasuminensis*. Small benthic fragilarioid species were also common in the shallower VOYA lakes.

3) Diatom-inferred reconstructions of TP, pH, and EC25 showed strong concordance with measured water quality parameters. Lakes in VOYA are generally oligo- to mesotrophic, circumneutral to slightly acidic, and have low conductivity.

4) In most VOYA lakes, changes in diatom communities between 2006 and 2010 based on squared chord distances were low. Three of VOYA's shallow lakes, Ek, Jorgens, and Ryan, showed higher levels of floristic change. In Ek Lake, increases in the planktonic species *Discostella stelligera* suggest shallower or less frequent mixing, and increases of benthic species in the very shallow Ryan Lake may also suggest less frequent mixing.

5) Surface sediment diatom communities from VOYA lakes were passively plotted on the species-environment ordination of the GLKN lakes to explore what environmental factors may be driving changes in modern diatom communities. Trajectories for the deeper lakes of VOYA (e.g., Cruiser, Little Trout) and two shallow lakes that had relatively high floristic change (Ek, Jorgens) suggest slight increases in pH, EC25, and nutrients (TP, NH₄, NO₃/NO₂).

6) Comparison of 2010 repeat samples with sediment records from lakes cored in 2006 at VOYA (Cruiser, Ek, Peary) show that recent samples from these lakes continue the trend of higher biological variability among sediment samples deposited after 1980.

7) The 2010 repeat samples suggest that the shallow lakes of VOYA may be showing the most rapid change; there is high biological variability between sampling dates (2006 vs. 2010) in both surface sediments and in post-1980 sediment core samples. These changes are difficult to capture with current water quality monitoring and might be explored in greater depth using buoyed sensors and/or modeling to better understand the extent, response and drivers of inter-annual variability.

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Introduction

In 2005, a lakes biomonitoring program was begun in conjunction with a network-wide water quality monitoring program to utilize sediment diatom assemblages to document change in lakes within the Great Lakes Network (GLKN) parks. The design of the project incorporated, first, a paleolimnology component to understand the ecological history of lakes in the GLKN parks. A single piston core that preserved approximately 200 years of sedimentation was recovered from select network lakes; in VOYA, Ek, Peary, and Cruiser lakes were cored in 2006. Interpretations of historical changes within the cores were based on changes in core geochemistry, sedimentation rates, and diatom communities to develop a timeline of change for each lake.

Notable among the results was the identification of recent changes in biological communities of wilderness lakes that may be related to climate drivers (Edlund et al. 2011).

The second component of the diatom biomonitoring program was the construction of diatom inference models with which to estimate various water quality parameters from sediment diatom assemblages. Recent diatom communities were collected from a calibration set of 60 GLKN lakes and the species-environment relationships examined (Ramstack et al. 2008, Edlund et al. 2011). The water quality parameters of TP, pH, and EC25 were shown to explain significant independent variation in the surface sediment diatom assemblages, and weighted averaging inference models were created for each of these parameters (Birks et al. 1990).

The final step in the biomonitoring program involves the repeat collection of surface sediment diatom assemblages from the GLKN lakes every three to five years (Edlund et al. 2011). The surface sediments represent 3-5 years of sediment accumulation and are analyzed for their diatom communities. Numerical analysis of the surface sediments includes applying diatom inference models to estimate recent TP, pH, and EC25 trends, followed by estimates of floristic change between the repeat and most recent surface sediment collection using the squared chord distance metric (Bennion et al. 2004, Simpson et al. 2005, Ramstack et al. 2008). Passive plotting of repeat surface sediment assemblages on ordinations of the GLKN diatom calibration set provides trajectories of change between the repeat and previous surface sediments and the opportunity to consider potential abiotic gradients that might be driving change in the diatom communities (Edlund et al. 2011).

In this report we provide results of diatom analysis of repeat surface sediment samples collected from 16 lakes in Voyageurs National Park. The recent samples are compared to sediment cores collected from three VOYA lakes, surface sediments collected in 2006, and water quality measures made between 2006 and 2010 (Elias and VanderMeulen 2008, Elias 2009, Edlund et al. 2011, Elias and Damstra 2011).

Methods

Water Quality Sampling

Sampling for physical and water chemistry parameters took place three times on each index lake during field years 2006-2010 in VOYA. Other lakes were sampled at less frequent intervals, for fewer parameters, and not in every sampling year (Elias and VanderMeulen 2008, Elias 2009, Elias and Damstra 2011). Water quality sampling and analytical methods followed Elias et al. (2008).

Surface Sediment Collection

A line-operated gravity corer was deployed from an anchored boat to collect the upper 0-1 cm and 1-2 cm of sediment at the same site that water quality was measured. Surface sediment collections were made between 30 July and 26 August 2010 from 16 VOYA lakes (Table 1). These sediments represent a spatially and temporally integrated assessment of biological remains and lake conditions during the past 3-5 years. Collection sites were located by global positioning system (GPS) to allow resampling in the same location in subsequent years; sampling sites always target central depositional basins in each lake (Ramstack et al. 2008). After subsampling, all sediment samples were refrigerated, transported to the St. Croix Watershed Research Station, Science Museum of Minnesota and processed for diatoms. Remaining sample material was subsequently freeze-dried and archived in scintillation vials at the St. Croix Watershed Research Station.

Table 1. VOYA lakes and date and location of sampling where surface sediments were collected in 2010. Core depths represent cm below sediment-water interface.

Lake	Date YYYYMMDD	Depth (cm)	UTM_X	UTM_Y
Tooth	20100730	0-1	526404	5360662
Mukooda	20100729	0-1	538042	5353548
Peary	20100819	0-1	516921	5374648
Oslo	20100817	0-1	514273	5373781
War Club	20100824	0-1	501225	5376018
Agnes	20100825	0-1	513938	5368312
Ek	20100825	0-1	512156	5368539
Brown	20100817	0-1	515043	5373668
Ryan	20100819	0-1	521633	5374013
Quarterline	20100826	0-1	511447	5369321
Cruiser	20100818	0-1	513783	5371765
Little Trout	20100823	0-1	535187	5360672
Jorgens	20100826	0-1	511235	5370116
O'Leary	20100823	0-1	534574	5362692
Locator	20100824	0-1	499729	5376439
Locator	20100824	0-2	499729	5376439
Shoepack	20100816	0-1	508321	5371725
Shoepack	20100816	0-2	508321	5371725

Among VOYA lakes where Pb-210 dated cores have been recovered (Ramstack et al. 2003, Edlund et al. 2011), two study lakes (Locator and Shoepack) have slightly higher sedimentation rates compared to the others. Because of this, concerns have been raised that the 0-1 cm increment would not provide an integrated sample of the diatom communities for the last 3-5 years as was noted in SLBE and PIRO lakes (Edlund et al. 2011). For the 2010 VOYA samples, both a 0-1 cm sample and a 0-2 cm sample were taken from the Locator and Shoepack gravity cores for processing and analysis of diatoms.

Sediment Processing and Diatom Analysis

For diatom analysis, sediment samples were prepared by placing approximately 0.25 cm³ of homogenized sediment in a 50 cm³ polycarbonate centrifuge tube and adding 2-5 drops of 10% v/v HCl solution to dissolve carbonates. Organic material was subsequently oxidized by adding 10 ml of 30% hydrogen peroxide and heating for 3 hours in a 85°C water bath. After cooling the samples were rinsed with deionized water to remove oxidation byproducts. Aliquots of the remaining material, which contains the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium (Ramstack et al. 2008).

Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification (full immersion optics of NA 1.4). A minimum of 400 valves was counted in each sample. Identification of diatoms relied on floras and monographs such as Hustedt (1927-1966, 1930), Patrick and Reimer (1966, 1975), Collins and Kalinsky (1977), Camburn et al. (1978, 1984-1986), Krammer and Lange-Bertalot (1986-1991), Cumming et al. (1995), Reavie and Smol (1998), Camburn and Charles (2000), Fallu et al. (2000), and the primary literature (e.g., Koppen 1975). For major taxa, digital images were taken to achieve consistent taxonomy. All diatom counts were converted to percentage abundances by taxon; abundances are reported relative to total diatom counts in each sample (Edlund et al. 2011).

Numerical Analysis

Several numerical and modeling techniques were used to analyze the relationships between the 2010 surface sediment diatom assemblages and monitored water quality data, surface sediment diatoms sampled in 2006, and historical diatom assemblages in long sediment cores collected at VOYA in 2006 (Edlund et al. 2011).

First, transfer functions that use diatom assemblages to estimate water quality parameters were applied to all 2010 VOYA surface sediment diatom assemblages to estimate epilimnetic pH, TP, and EC25. The transfer functions were developed earlier for the GLKN lakes (Edlund et al. 2011) using weighted averaging (WA) regression with inverse deshrinking, and bootstrap error estimation (Birks et al. 1990) with the software C2 (Juggins 2003). The transfer functions calculate each taxon's environmental optimum and tolerance for specific environmental variables. To reconstruct a water quality parameter from a diatom community, each taxon's environmental optimum was weighted by its relative abundance in the sample; the summed weighted optima of the entire species assemblage in the diatom community represent the diatom-inferred water quality estimate (Birks et al. 1990).

Second, to determine the amount of floristic or community change in the diatom communities between the 2010 repeat surface sediments, the 2006 surface samples, and the long cores taken from Cruiser, Ek, and Peary lakes in 2006, we used the squared chord distance measure. Squared chord distance is a dissimilarity measure with values ranging from 0 (samples are exactly the same) to 2 (samples are completely different). Meaningful change can be assessed using percentile cutoffs from randomly generated, approximately normally distributed data, that range from the lower to upper limits of the squared chord distance (0 to 2) (Bennion et al. 2004, Simpson et al. 2005). As such, squared chord distances greater than 0.39 to represent meaningful floristic change; this value was determined by Simpson et al. (2005) and Simpson (personal communication) and represents the fifth percentile in distribution of pairwise comparisons based on the above method. Squared chord distances less than the fifth percentile limit represent low floristic change (Bennion et al. 2004, Simpson personal communication). All 2010 samples were compared to their corresponding surface sample taken in 2006. For Cruiser, Ek, and Peary lakes, the squared chord distance from the 2006 to 2010 surface sample was further compared to long sediment core samples (cores collected in 2006) by comparing the floristic change between pre-Euro-American samples and the core top and the floristic change between park formation and the core top as outlined in Edlund et al. (2011).

Third, to explore potential environmental drivers of biological change, diatom assemblages from the 2010 repeat samples were passively plotted on the GLKN calibration set CCA. The trajectory between the 2006 surface sediment sample and the 2010 repeat sample from each lake was identified and considered in relationship to the main environmental axes that explained independent variation in the GLKN surface sediment calibration set (Ramstack et al. 2008, Edlund et al. 2011). These analyses were implemented with the software package R (Ihaka and Gentleman 1996).

Last, for the three VOYA lakes for which we have long sediment cores (Cruiser, Ek, and Peary), we reran a DCA (R software; Ihaka and Gentleman 1996) on each core with the 2010 repeat sample included. All core depths were plotted in ordinate space (by ^{210}Pb date) and their relationships and variability used to identify sample groups, ecological variability among core samples, and periods of change, including recent change.

Results

Water Quality (VOYA 2006-2010)

Although many physical and water quality parameters are measured in the GLKN lakes, we consider here only the water quality parameters that showed strong independent relationships with diatom assemblages based on the initial diatom biomonitoring study (Edlund et al. 2011). These parameters include TP, pH, and EC25. Mean annual water quality data are summarized from the literature for each of these parameters based on sampling that occurred on VOYA lakes from 2006-2010 (Table 2; Elias and VanderMeulen 2008, Elias 2009, Elias and Damstra 2011).

Table 2. Summary of mean annual water quality measures from sixteen lakes at Voyageurs National Park, Minnesota. Eight index lakes were sampled three times annually from 2006-2010, whereas other lakes were not always sampled each year (data from Elias and VanderMeulen 2008, Elias 2009, Elias and Damstra 2011).

Lake	Mean annual TP ($\mu\text{g/L}$)			Mean annual EC25 ($\mu\text{S/cm}$)			Mean annual pH		
	<i>min</i>	<i>max</i>	<i>Sampling yrs</i>	<i>min</i>	<i>max</i>	<i>Sampling yrs</i>	<i>min</i>	<i>max</i>	<i>Sampling yrs</i>
Agnes	23	23	06	22	24	06-07	6.3	6.4	06-07
Brown	7	14	06-10	19	23	06-10	6.8	7.3	06-10
Cruiser	3	5	06-10	19	21	06-10	7.1	7.7	06-10
Ek	16	24	06-10	26	33	06-10	7.0	7.6	06-10
Jorgens	11	11	06	24	26	06-07	6.9	7.2	06-07
Little Trout	4	5	06-10	34	37	06-10	7.7	7.8	06-10
Locator	7	13	06-10	24	26	06-10	6.8	7.5	06-10
Mukooda	8	8	06	53	57	06-07	7.9	8.0	06-07
O'Leary	9	9	06	60	66	06-07	7.7	8.7	06-07
Oslo	8	8	06	20	23	06-07	7.0	7.3	06-07
Peary	15	24	06-10	24	31	06-10	7.0	7.6	06-10
Quarterline	16	16	06	24	26	06-07	6.4	6.5	06-07
Ryan	9	11	06-10	23	33	06-10	6.8	7.2	06-10
Shoepack	17	29	06-10	21	27	06-10	6.3	7.0	06-10
Tooth	9	9	06	29	32	06-07	6.9	6.9	06-07
War Club	8	8	06	25	27	06-07	6.8	7.1	06-07

Mean annual TP in VOYA lakes between 2006 and 2010 (Table 2) ranged from 3 $\mu\text{g/l}$ (Cruiser Lake; 2008) to 29 $\mu\text{g/L}$ in Shoepack Lake (2006). Among the index lakes, there are no obvious trends in mean annual TP from 2006-2010. Mean annual EC25 measured in VOYA lakes between 2006 and 2010 (Table 2) ranged from 19 $\mu\text{S/cm}$ (Brown and Ryan lakes; 2010) to 66 $\mu\text{S/cm}$ in O'Leary Lake based on a single measurement taken in July 2007. Although the changes are not dramatic, mean annual values of EC25 may be dropping slowly in VOYA's index lakes (Table 2). Mean annual pH in VOYA lakes between 2006 and 2010 was as low as 6.3 (Shoepack Lake in 2010, Agnes Lake in 2006) and as high as 8.74 in O'Leary Lake based on a single yearly measure taken July 2007. Most VOYA index lakes had their highest mean annual pH in 2009.

Surface Sediment Diatom Assemblages

The diatom assemblages preserved in the 2010 surface sediments of the VOYA lakes comprise a diverse flora of almost 450 species. Dominating the flora are the planktonic forms *Tabellaria flocculosa* IIIp, *Discostella stelligera*, *Asterionella formosa*, *Aulacoseira ambigua*, *A. subarctica*, *A. tenella*, *A. italica*, and the softwater form *Eunotia zasuminensis*. Other diatoms are benthic species, including the benthic fragilarioids *Staurosira construens* var. *venter*, *Staurosirella pinnata* and its var. *lancettula*, *Pseudostaurosira brevistriata*, and *P. microstriata*. The predominant diatoms (>5% relative abundance in order from the most abundant) in each lake's 2010 sediment sample are shown in Table 3.

Table 3. Predominant diatoms (>5% relative abundance) in sediment samples collected from lakes at Voyageurs National Park, Minnesota, in 2010.

Index Lakes	Diatoms (in order of abundance)
Brown	<i>Aulacoseira tenella</i> , <i>Discostella stelligera</i> , <i>Asterionella formosa</i> , <i>Aulacoseira ambigua</i>
Cruiser	<i>Discostella stelligera</i> , <i>Asterionella formosa</i> , <i>Synedra radians</i>
Ek	<i>Discostella stelligera</i> , <i>Asterionella formosa</i> , <i>Aulacoseira ambigua</i> , <i>Staurosira construens</i> var. <i>venter</i> , <i>Aulacoseira tenella</i>
Little Trout	<i>Discostella stelligera</i> , <i>Cyclotella ocellata</i> , <i>Synedra radians</i> , <i>Cyclotella michiganiana</i>
Locator	<i>Asterionella formosa</i> , <i>Tabellaria flocculosa</i> IIIp, <i>Discostella stelligera</i> , <i>Aulacoseira tenella</i>
Peary	<i>Aulacoseira tenella</i> , <i>Tabellaria flocculosa</i> IIIp, <i>Asterionella formosa</i> , <i>Aulacoseira ambigua</i> , <i>Discostella stelligera</i> , <i>Eunotia zasuminensis</i>
Ryan	<i>Staurosira construens</i> var. <i>venter</i> , <i>Staurosirella pinnata</i> , <i>Pseudostaurosira brevistriata</i> , <i>Pseudostaurosira microstriata</i> , <i>Aulacoseira laevisissima</i> , <i>Aulacoseira pseudoamericana</i> , <i>Staurosirella pinnata</i> var. <i>lancettula</i>
Shoepack	<i>Eunotia zasuminensis</i> , <i>Aulacoseira ambigua</i> , <i>Aulacoseira tenella</i> , <i>Asterionella formosa</i> , <i>Aulacoseira italica</i> , <i>Discostella stelligera</i> , <i>Tabellaria flocculosa</i> IIIp
Non-Index Lakes	
Agnes	<i>Eunotia zasuminensis</i> , <i>Aulacoseira tenella</i> , <i>Asterionella formosa</i> , <i>Staurosira construens</i> var. <i>venter</i>
Jorgens	<i>Staurosira construens</i> var. <i>venter</i> , <i>Asterionella formosa</i>
Mukooda	<i>Tabellaria formosa</i> IIIp, <i>Asterionella formosa</i> , <i>Stephanodiscus minutulus</i> , <i>Stephanodiscus hantzschii</i> , <i>Discostella stelligera</i> , <i>Fragilaria crotonensis</i> , <i>Aulacoseira italica</i>
O'Leary	<i>Asterionella formosa</i> , <i>Stephanodiscus hantzschii</i> , <i>Fragilaria crotonensis</i> , <i>Stephanodiscus minutulus</i> , <i>Aulacoseira subarctica</i>
Oslo	<i>Aulacoseira tenella</i> , <i>Discostella stelligera</i> , <i>Asterionella formosa</i> , <i>Tabellaria flocculosa</i> IIIp, <i>Eunotia zasuminensis</i>
Quarterline	<i>Staurosira construens</i> var. <i>venter</i> , <i>Aulacoseira tenella</i> , <i>Asterionella formosa</i> , <i>Eunotia zasuminensis</i>

Table 3. Predominant diatoms (>5% relative abundance) sediment samples collected in 2010 from lakes at Voyageurs National Park, Minnesota (continued).

Non-Index Lakes	Diatoms (in order of abundance)
Tooth	<i>Tabellaria flocculosa</i> Illp, <i>Asterionella formosa</i> , <i>Discostella stelligera</i> , <i>Aulacoseira tenella</i> , <i>Puncticulata bodanica</i> var. <i>lemanica</i>
War Club	<i>Asterionella formosa</i> , <i>Discostella stelligera</i> , <i>Aulacoseira tenella</i> , <i>Tabellaria flocculosa</i> Illp

Ecological Change in VOYA Lakes (2006-2010)

Diatom-inferred Water Quality Measures

Transfer functions developed by Edlund et al. (2011) for estimating TP, EC25, and pH were applied to the diatom assemblages from 16 VOYA surface sediments collected in 2010 (Table 4). Estimates of diatom-inferred TP (DI-TP) suggested most of the VOYA lakes are oligotrophic to mesotrophic with DI-TP ranging from 5.5 µg/L TP in Jorgens Lake to 15.6 µg/L TP in Ryan Lake. Most lakes reconstructed very close to measured TP values with model error estimates easily incorporating the range of measured annual means (Table 4A). Three lakes showed TP reconstructions that were less consistent with measured values. TP was only sampled in 2006 in Agnes Lake, which had a mean annual TP of 23.0 µg/L. Agnes Lake DI-TP was lower at 14.1 µg/L based on the 2010 repeat sample. Water quality was sampled every year in Peary Lake from 2006-2010 with TP ranging from 15.0 to 23.6 µg/L. The DI-TP was somewhat lower at 11.2 µg/L but still in the mesotrophic range and model error estimates captured the lower range of measured TP. Shoepack Lake had annual mean TP of 16.8 to 29.0 µg/L from 2006 to 2010, whereas DI-TP reconstructed somewhat low at 13.9 µg/L. Again, model error estimates captured the lower range of measured TP.

Diatom inferred EC25 ranged from 17.2 µS/cm for the Locator Lake 0-2 cm sample to 63.7 µS/cm for Ryan Lake. DI-EC25 estimates were very similar to measured conductivity (Table 4B) except in two lakes. Jorgens Lake has a DI-EC25 estimate of 49.2 µS/cm whereas measured conductivity was ranged only from 24-26 µS/cm. Similarly, Ryan Lake had DI-EC25 of 63.7µS/cm, well above the 23 to 33 µS/cm measured between 2006 and 2010. The sediment assemblage in both of these lakes was dominated by *Staurosira construens* var. *venter*, a benthic diatom, which helped drive the conductivity estimates a bit high.

Estimates of DI-pH showed the VOYA lakes to be circumneutral and ranged from 6.72 in Agnes Lake to 7.68 in Little Trout Lake. DI-pH values for most lakes were very close to measured pH records taken from 2006-2010. Two VOYA lakes with rather high measured pH, Mukooda and O'Leary lakes, gave DI-pH estimates that were too low. The lakes stand out because of the abundance of small planktonic *Stephanodiscus* species and *Fragilaria crotonensis* in their sediments. In contrast, the DI-pH of Quarterline Lake was slightly higher than the measured pH values that only ranged from 6.45 to 6.5.

Diatom Community Change

To measure biological community change, the squared chord distance was calculated between diatom assemblages in surface sediment samples collected in 2010 and 2006. For the 16 VOYA

lakes, most showed low levels of community change (Figure 1). Only three shallow lakes, Ek ($Z_{\max}$ =5.7 m), Jorgens ($Z_{\max}$ =5.8 m), and Ryan ($Z_{\max}$ =3.6 m) showed high levels of floristic change between 2006 and 2010 (Figure 1).

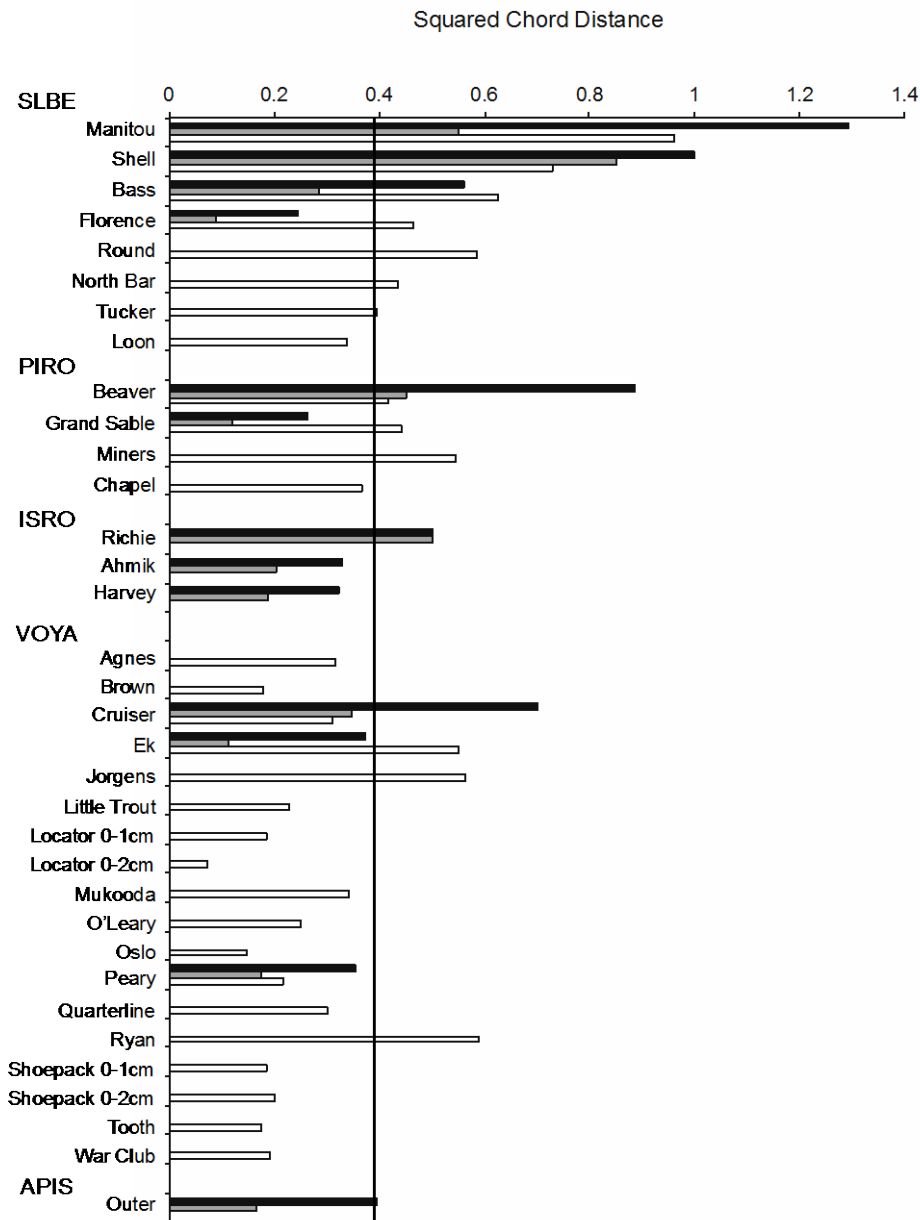


Figure 1. Plot of squared chord distances for long sediment cores and surface repeat samples from GLKN park lakes. Black filled bars represent squared chord distance between presettlement samples and top of core samples, gray filled bars represent squared chord distance between samples deposited at park formation and top of core samples, white bars represent distance between calibration set samples collected in 2005 (SLBE and PIRO lakes; reported earlier in Edlund et al. 2011) or 2006 (VOYA lakes) compared to surface sediment samples collected in 2008 (PIRO) or 2009 (SLBE) or 2010 (VOYA). The line at 0.39 represents the cutoff for significant floristic change (see text and Simpson et al. 2005).

We considered how the diatoms communities of each of these three lakes changed between 2006 and 2010. In Ek Lake, there were no major species lost between 2006 and 2010; however, *Aulacoseira tenella* was added to the flora in 2010 at 6.1% relative abundance. Taxa that showed marked changes in relative abundance (>2%) in Ek Lake included: *Discostella stelligera* (2006 to 2010; 8.6% to 12.7%), *Asterionella formosa* (17.8% to 13.6%), *Staurosira construens* var. *venter* (12.3% to 6.9%), *Tabellaria flocculosa* IIIp (10.9% to 4.6%), *Navicula kuelbsii* (0% to 2.1%), and *Synedra radians* (0% to 2.1%). The increases in *Discostella stelligera* coupled with decreases in the benthic taxa may indicate less frequent or shallower mixing of Ek Lake (Saros et al. 2012). *Discostella stelligera* also responds to nitrogen additions (Saros et al. 2012); exports of N from boreal catchments have been shown to be increasing at ISRO (Toczydlowski and Stottlemeyer 2009).

The only major species replacement in Jorgens Lake between 2006 and 2010 was the loss of the benthic diatom *Pseudostaurosira microstriata*, which was present at 7.6% relative abundance in 2006 and not found in the 2010 sample. Other diatoms that shifted in relative abundance >2% between 2006 and 2010 included: *Staurosira construens* var. *venter* (2006 to 2010; 7.4% to 20.6%), *Navicula minima* (<1% to 3.25%), *Aulacoseira ambigua* (6.4% to 2.2%), *Staurosirella pinnata* (4.7% to 1.5%), *Aulacoseira laevisissima* (3.4% to 0.7%), and *Aulacoseira perglabra* (3.6% to 0.7%). From an ecological standpoint, the primary shifts in diatom composition are among the benthic taxa with little change in plankton composition between 2006 and 2010 among the predominant species (*Asterionella formosa*, *Tabellaria flocculosa* IIIp, and *Aulacoseira ambigua*). As such we have less context for interpreting these changes than in Ek Lake.

Among the VOYA lakes, Ryan Lake had the greatest squared chord distance between 2006 and 2010 and saw the loss of one taxon and the gain of several others in that period. *Synedra exilis* was found at 20.5% abundance in 2006 but was missing from the 2010 flora. In contrast, diatoms that became prevalent in the 2010 sample but were absent from the 2006 sample included *Pseudostaurosira microstriata* (2010; 7.1%), *Aulacoseira laevisissima* (2010; 5.7%), *Aulacoseira perglabra* (2.6%) and *Aulacoseira islandica* (2010; 2.2%). Many diatoms also showed more than 2% change in relative abundance between 2006 and 2010 including: *Staurosira construens* var. *venter* (2006 to 2010; 12.1% to 20.5%), *Staurosirella pinnata* (6.4 to 9.7), *Pseudostaurosira brevistriata* (4.8 to 9.3), *Aulacoseira pseudoamericana* (2.3% to 5.5%), *Staurosirella pinnata* var. *lancettula* (<1% to 5.1%), and *Aulacoseira ambigua* (6.2% to 2.2%). These changes contributed to the large squared chord measures in Ryan Lake and spotlight large increases in benthic species. Because these shallow lakes are showing the greatest ecological change in diatom communities, some additional sampling effort might be recommended to look in more detail at intra- and inter-annual variability among nutrient, clarity, and mixing trends.

Directionality of change using calibration set CCA

Changes in diatom communities were further explored by passively plotting the 2010 surface sediment assemblages on the CCA of species-environment relationships among all GLKN lakes (Figures 2-5; Edlund et al. 2011). By noting the direction of change between the 2006 and 2010 samples, the trajectory of community change could be considered with regard to the primary environmental gradients that determine diatom turnover. In comparison to some of the large changes seen in repeat surface sediments from SLBE and PIRO lakes (Edlund et al. 2011), the lakes of VOYA showed much more modest change. Most of the lakes that show change shifted

along one of two gradients (Figures 2-5). Lakes such as Jorgens, Cruiser, Little Trout, O'Leary and Ryan move left along CCA axis 1, which suggests minor increases in pH, EC25, and less so nutrients (TP, NH₄, NO₃/NO₂). These lakes are primarily the deeper lakes of VOYA (Cruiser, Little Trout, O'Leary), although Jorgens and Ryan are shallow systems. Two other shallow lakes, Ek and Brown, move right along CCA Axis 1 suggesting a slight shift downward in nutrients, pH and EC25 and perhaps a slight increase in DOC. Other VOYA lakes show very small shifts in the context of the environmental gradients seen among the GLKN lakes.

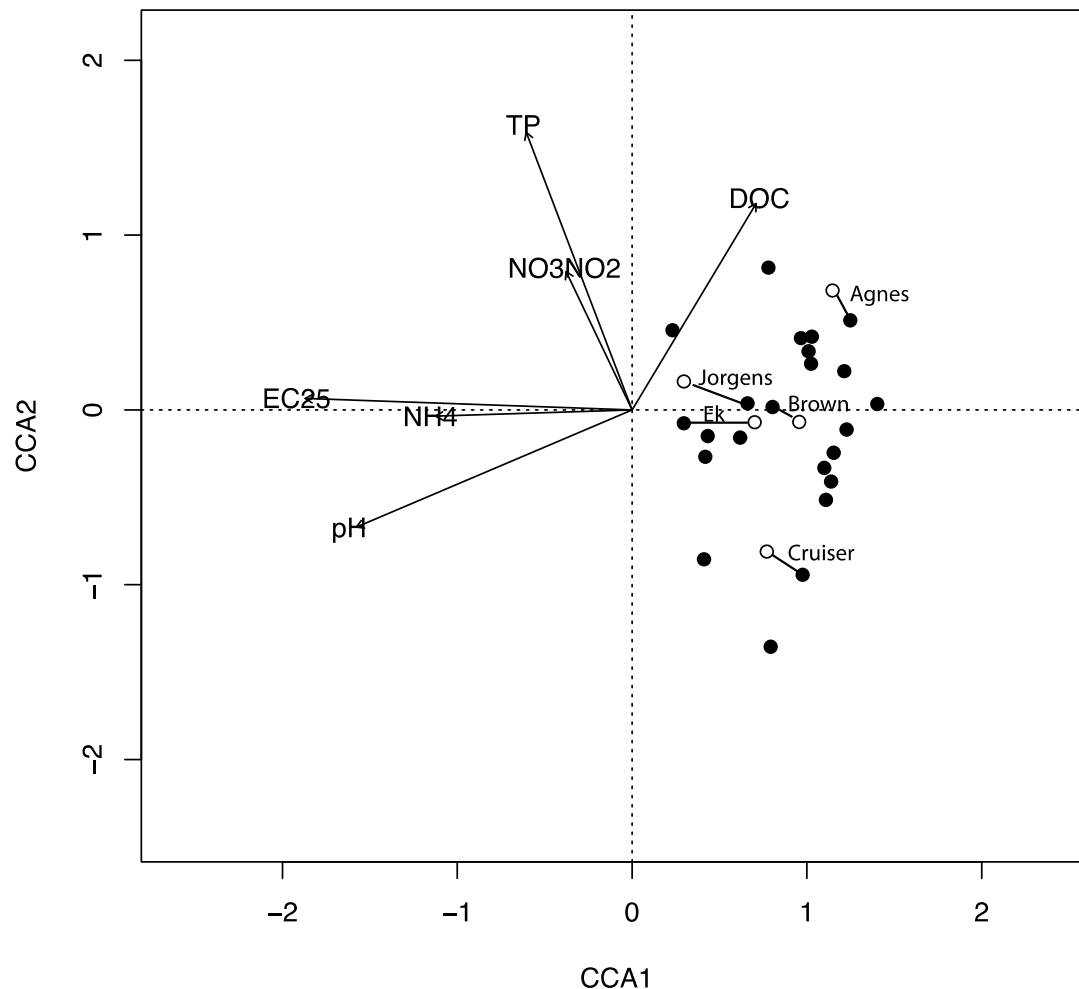


Figure 2. The 2010 repeat surface sediment samples from VOYA lakes (Agnes, Brown, Cruiser, Ek, and Jorgens) passively plotted on the CCA of the GLKN diatom calibration set. Vectors show environmental variables that explain significant independent variation in diatom abundance. Filled circles represent surface sediment samples taken in 2006 from all VOYA lakes, open circles represent repeat surface sediment samples taken in 2010 from VOYA lakes (Agnes, Brown, Cruiser, Ek, and Jorgens). Chords connect the 2006 and 2010 samples from labeled lakes.

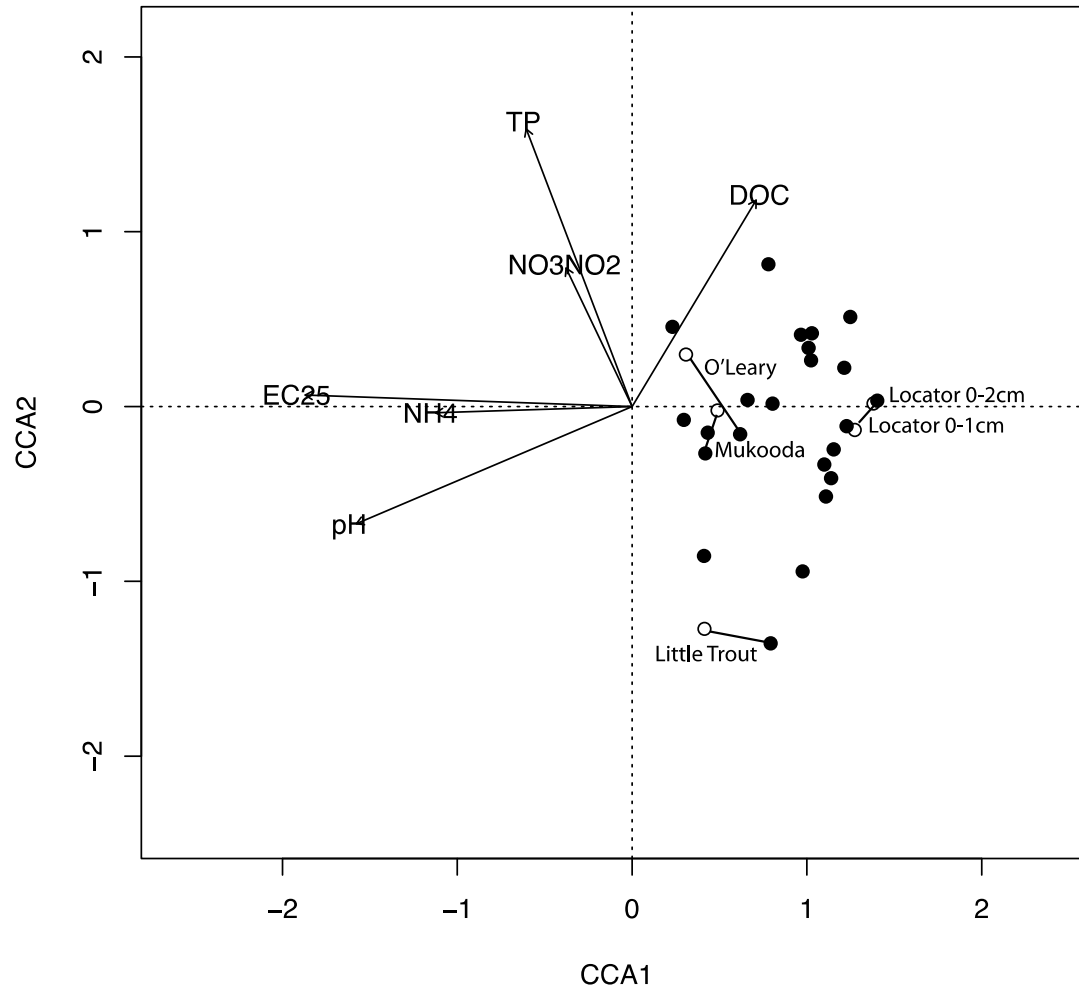


Figure 3. The 2010 repeat surface sediment samples from VOYA lakes (Little Trout, Locator 0-1 cm, Locator 0-2 cm, Mukooda, and O'Leary) passively plotted on the CCA of the GLKN diatom calibration set. Vectors show environmental variables that explain significant independent variation in diatom abundance. Filled circles represent surface sediment samples taken in 2006 from all VOYA lakes, open circles represent repeat surface sediment samples taken in 2010 from VOYA lakes (Little Trout, Locator 0-1 cm, Locator 0-2 cm, Mukooda, and O'Leary). Chords connect the 2006 and 2010 samples from labeled lakes.

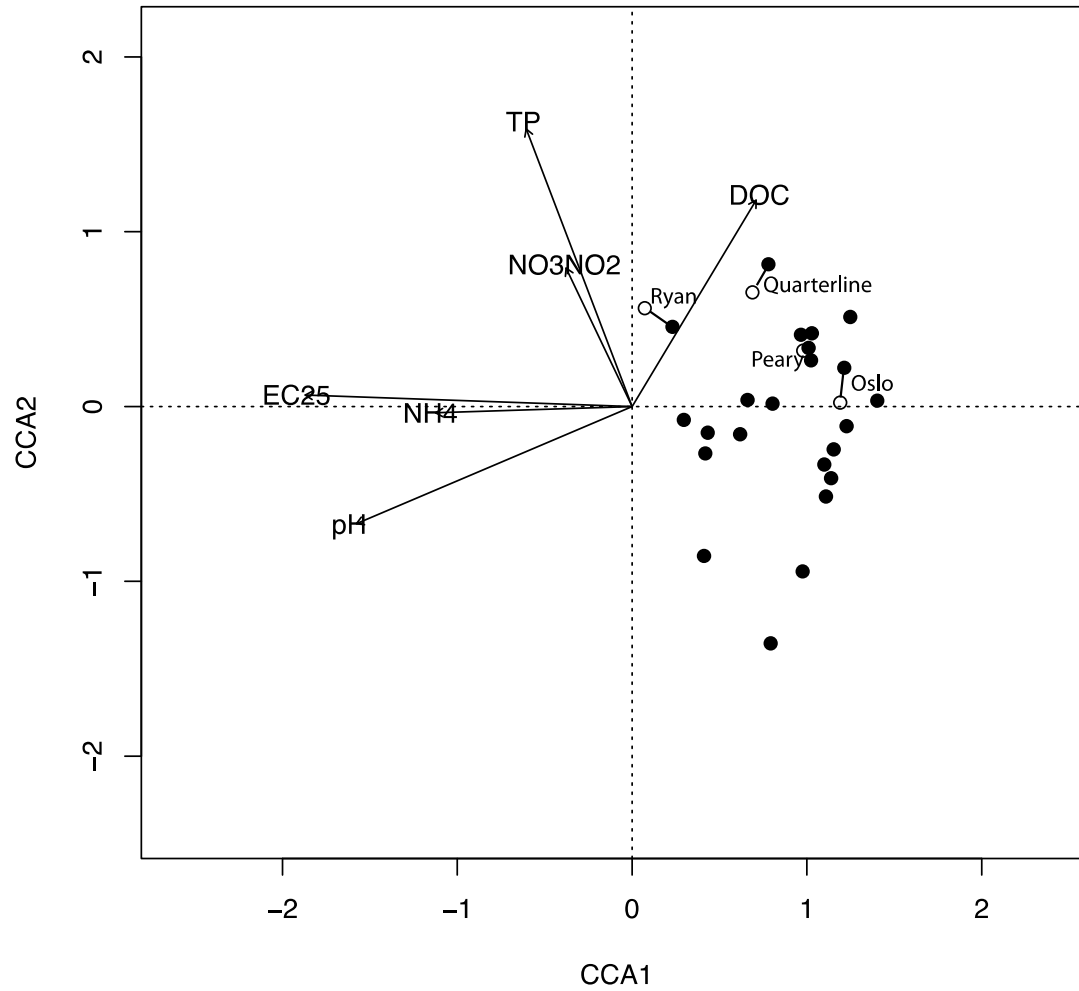


Figure 4. The 2010 repeat surface sediment samples from VOYA lakes (Oslo, Peary, Quarterline, and Ryan) passively plotted on the CCA of the GLKN diatom calibration set. Vectors show environmental variables that explain significant independent variation in diatom abundance. Filled circles represent surface sediment samples taken in 2006 from all VOYA lakes, open circles represent repeat surface sediment samples taken in 2010 from VOYA lakes (Oslo, Peary, Quarterline, and Ryan). Chords connect the 2006 and 2010 samples from labeled lakes.

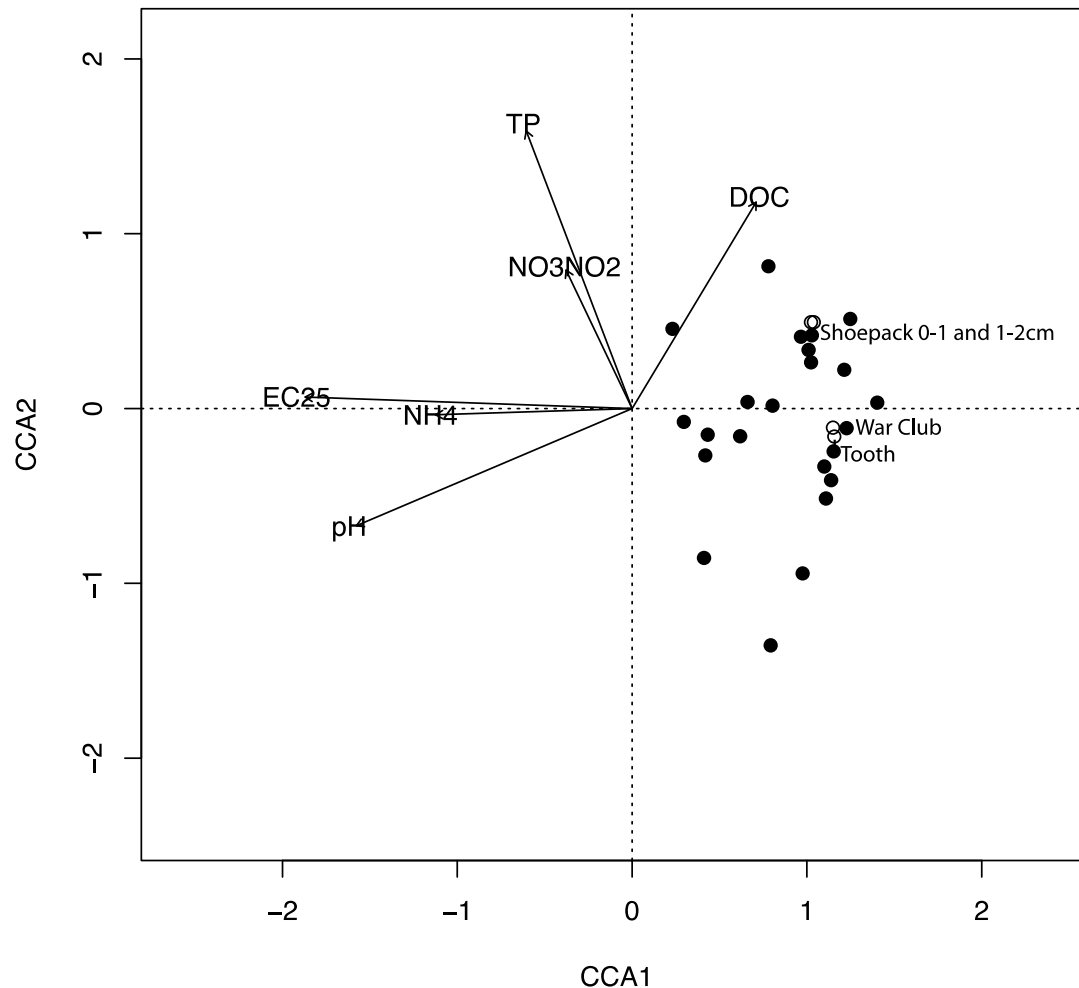


Figure 5. The 2010 repeat surface sediment samples from VOYA lakes (Shoepack 0-1 cm, Shoepack 0-2 cm, Tooth, and War Club) passively plotted on the CCA of the GLKN diatom calibration set. Vectors show environmental variables that explain significant independent variation in diatom abundance. Filled circles represent surface sediment samples taken in 2006 from all VOYA lakes, open circles represent repeat surface sediment samples taken in 2010 from VOYA lakes (Shoepack 0-1 cm, Shoepack 0-2 cm, Tooth, and War Club). Chords connect the 2006 and 2010 samples from labeled lakes.

Environmental Change in Relation to Cored VOYA Lakes

Long cores were recovered from three VOYA lakes in 2006: Cruiser, Ek, and Peary. Squared chord distances were earlier estimated for pre-Euro American sediment assemblages and those deposited at the core top, and between samples from the time of park formation against assemblages from the core top (Edlund et al. 2011). For most lakes cored in the GLKN, including the three VOYA lakes, the amount of community change is greatest between the pre-Euro-American assemblages and the most recent core material. These historical measures of community change can be further compared to the squared chord distances calculated between the 2006 and 2010 VOYA surface samples. In Cruiser and Peary lakes, the amount of change between 2006 and 2010 is very similar to the amount of change between park formation (ca. 1975) and the 2006 core top. Note, however, that the amount of biological change in either

period did not exceed the cutoff level set for significant floristic change (see Figure 1). In contrast, between 2006 and 2010 the amount of floristic change in Ek Lake was significant and markedly higher than the change recorded in the Ek Lake long core between 1975 and 2006 or between Euro-American settlement and 2006. Factors that might be driving or exacerbating the recent changes in Ek Lake are discussed above.

Last, we have plotted the 2010 surface sediments from Cruiser, Ek, and Peary on their respective DCA plots of their 2006 sediment cores (Figures 6-8). In Cruiser Lake, the 2010 surface sample plotted quite distant along DCA axis 2 from the top two samples in the 2006 core (Figure 6). However, it should be noted that the Cruiser Lake site that was cored in 2006 is not in the same basin as the water quality monitoring site. As such, we would expect additional variability between the surface samples and core samples due simply to differences in the two depositional environments. In Ek Lake, the 2010 surface sample similarly plots distant along DCA axis 2 from the core top, which was Pb-210 dated at ca. 2000 (Figure 7). This further supports the significant changes that were seen between the 2006 and 2010 surface sediment assemblages from Ek Lake. Several lines of evidence, including the relatively high variability of sediment core samples deposited since the 1980s and significant floristic change between 2006 and 2010, support enhanced monitoring efforts on Ek Lake to better understand what is driving recent changes in this wilderness lake. Peary Lake also shows higher variability in sediment core samples deposited since the 1980s, and the 2010 surface sample plots distant along DCA axis 2 from the topmost dated level (ca. 2001) in the Peary Lake core (Figure 8). However, we noted less dramatic changes between the surface sediments from 2006 and 2010 (see Figure 1).

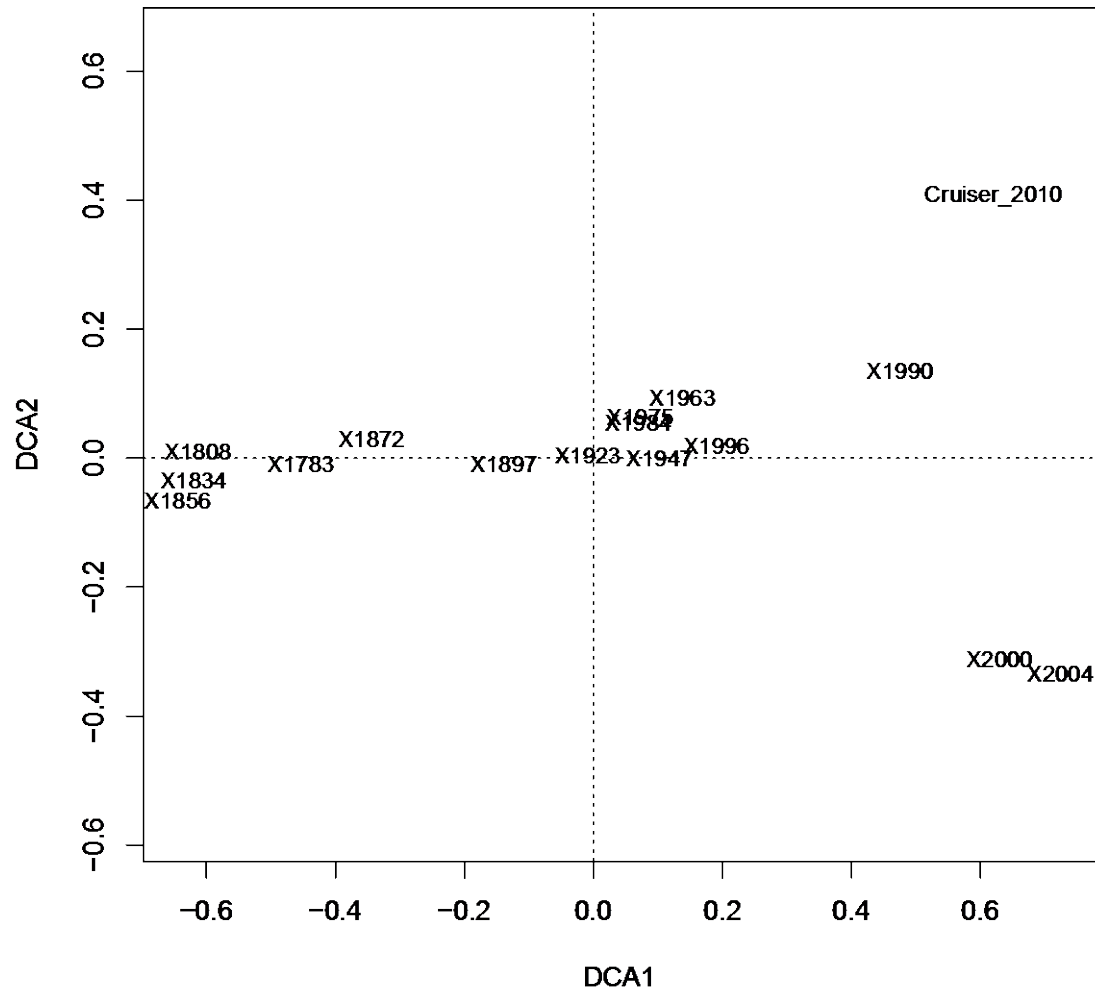


Figure 6. DCA of downcore diatom assemblages from Cruiser Lake core (VOYA, 1783-2004) including the 2010 repeat surface sample; axes 1 and 2 loadings plotted for core depths-dates.

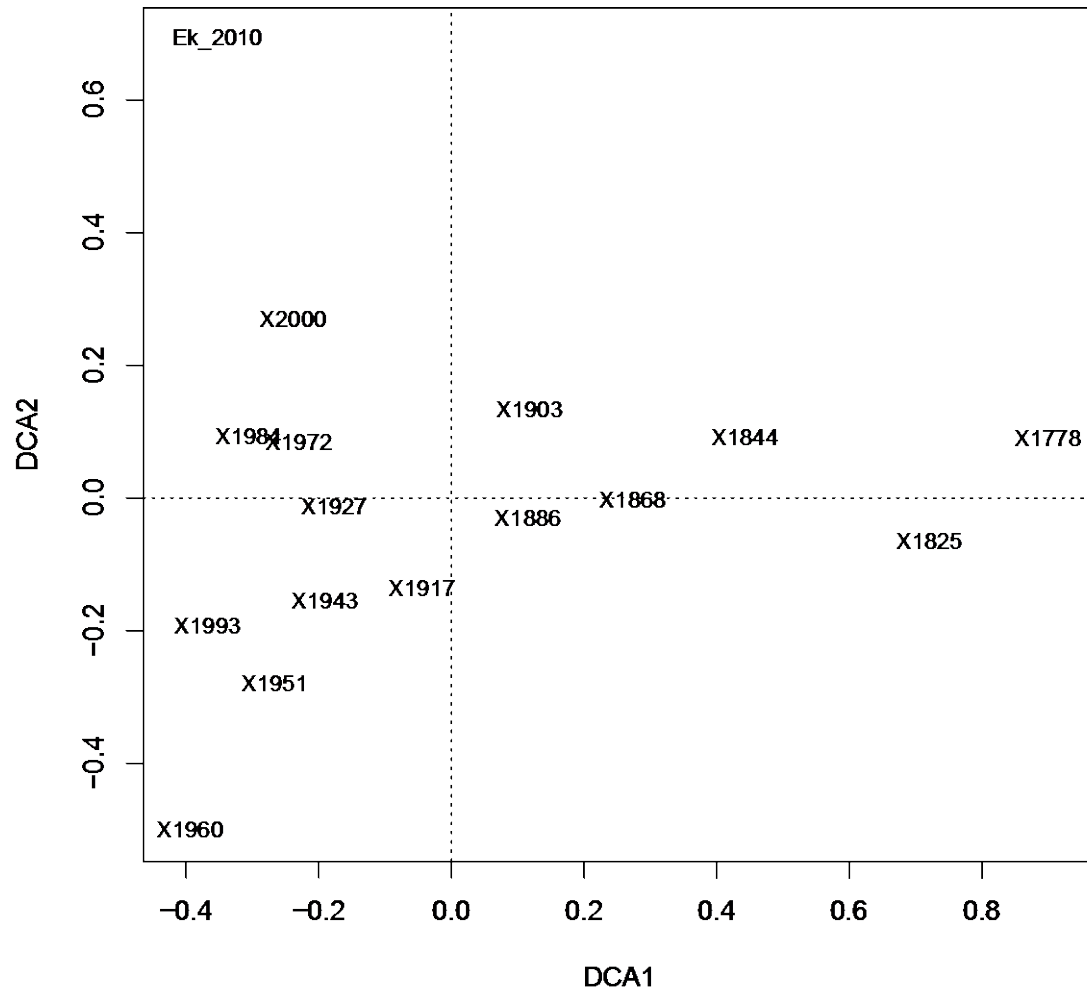


Figure 7. DCA of downcore diatom assemblages from Ek Lake core (VOYA, 1778-2000) including the 2010 repeat surface sample; axes 1 and 2 loadings plotted for core depths-dates.

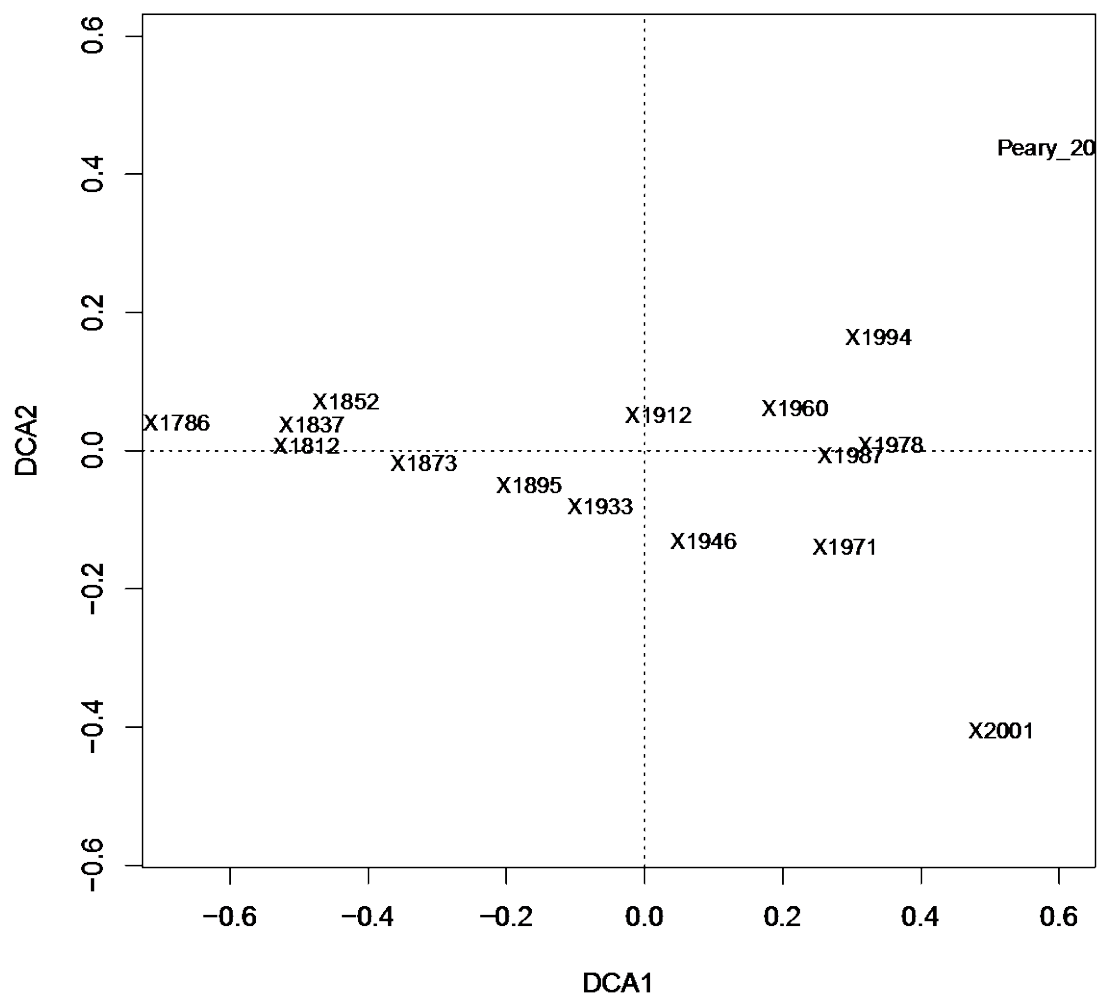


Figure 8. DCA of downcore diatom assemblages from Peary Lake core (VOYA, 1786-2001) including the 2010 repeat surface sample; axes 1 and 2 loadings plotted for core depths-dates.

Ecological Change in High Sedimentation Lakes (Locator, Shoepack)

The initial analysis of repeat surface sediment samples looked at samples collected in 2008 and 2009 against samples collected in 2005 at SLBE and PIRO (Edlund et al. 2011). Many of the lakes showed significantly high levels of floristic change between 2005 and 2008/2009 (see Figure 1). One potential cause of these high levels of change may be the result of the lakes in SLBE and PIRO having relatively high linear sedimentation rates. As such, the top 0-1 cm in a surface sediment collection can represent much less than even one year of sedimentation, thus comparisons of 0-1 cm repeat surface sediments may be comparing short-lived blooms rather than several years of sedimentation. Recommendations were made to sample 3-5 years of sediment accumulation in the surface sediment collections if possible for biomonitoring with diatom assemblages (Edlund et al. 2011). In VOYA lakes, sedimentation rates are typically very slow. Shoepack and Locator lakes are the only lakes that have higher linear sedimentation rates so we compared a 2010 sample of 0-1 cm and a 0-2 cm to the earlier 2006 surface sediment collection from each lake. The issue of large biological changes found in the analysis of repeat

samples at PIRO and SLBE was not evident in the 2010 VOYA samples. Both lakes, Shoepack and Locator, showed similar and low squared chord distances between the 2006 sample and the 0-1 cm and 0-2 cm samples collected in 2010 (see Figure 1), suggesting that changes that are identified in VOYA lakes are not simply an artifact of the surface sediment records being biased by potential preservation of sub-annual diatom productivity (Edlund et al. 2011). Similar tests are being run on the 2011 repeat samples collected from APIS, SACN, INDU, and MISS lakes.

Conclusions

The main goals of the repeat surface sediment approach and diatom analysis are to detect biological changes in the NPS lakes that are not sampled during regular WQ monitoring and potentially capture changes in the lakes through integrated biological sampling that are not detected with current WQ sampling. As such, this approach combines both traditional WQ monitoring and an integrated biological sampling to detect change. Pairing the two techniques, we are able to detect biological change, estimate trends in several WQ parameters (pH, TP, EC25) using diatom-inferred models, interpret change, generate hypotheses on why change is occurring, and potentially direct future research efforts and resources to more fully understand and respond to the changes. Repeat surface sediments collected in 2010 from 16 VOYA lakes were analyzed for diatom assemblages and compared to surface sediment samples collected from the same lakes in 2006 and to diatom communities preserved in three long sediment cores collected from Cruiser, Ek, and Peary lakes in 2006. Diatom inference models were applied to all repeat samples to estimate recent TP, pH, and EC25 values in VOYA lakes. Diatom-inferred estimates were very similar to measured WQ (2006-2010) in most lakes and supported that VOYA lakes are generally oligo- to mesotrophic, have low conductivity, and are circumneutral to slightly acidic. Floristic change between 2006 and 2010 was estimated with the squared chord distance and showed that three shallow lakes (Ek, Jorgens, Ryan) had significant floristic change between 2006 and 2010. Ecological changes seem to suggest shallower or less frequent mixing in the shallow lakes based on increases in *Discostella stelligera* (Ek Lake) and increased benthic diatoms (Ryan Lake). Ecological trajectories showing direction of environmental change were based on passive plots of the 2010 repeat samples on the CCA ordination of the full GLKN diatom species-environment calibration set.

Trajectories for the deeper lakes of VOYA (e.g., Cruiser, Little Trout) and two shallow lakes that had relatively high floristic change (Ek, Jorgens) suggest slight increases in pH, EC25, and nutrients (TP, NH₄, NO₃/NO₂) between 2006 and 2010; monitored pH and EC25 provide some support of these trends. Similar passive plots of the 2010 repeat samples on DCA ordinations of the three VOYA lakes that were cored in 2006 continued to support trends preserved in the cores since the 1980s of greater variability in diatom communities between samples. Greater within-lake variability in recent (post-1980) diatom communities and evidence that the shallow lakes of VOYA showed significant floristic changes between 2006 and 2010 support recommendations that additional efforts might be best directed at VOYA's shallow lakes. Current sampling is not able to assess all drivers of inter-annual variability or seasonal patterns of lake mixing; these might be explored in greater depth using buoyed monitors and/or modeling to better understand response and drivers of recent change in VOYA lakes.

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