



Minnesota diatomists: The first 150 years

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Abstract

Minnesota boasts over 12,000 lakes, most of glacial origin, three major continental drainage systems (Mississippi River to the Gulf of Mexico, Lake Superior via the other Great Lakes to the Atlantic Ocean, and the Red River of the North via the Nelson River, to Hudson Bay), and a diversity of landforms comprising seven major ecological regions. Such landscape and aquatic variability hosts a high diversity of diatoms, which have been studied for over 150 years. Diatom communities range from saline and eutrophic in the southwest agricultural lands, to oligotrophic and endemic forms in the cold waters of Lake Superior. Early diatom collections were distributed to reknowned diatomists such as C.G. Ehrenberg and H.L. Smith. Other botanists and phycologists, including Tilden, Eddy, and Drouet, were active in Minnesota but only rarely included diatoms in their studies. Interest in Minnesota diatoms increased in the latter half of the 20th century with taxonomic and floristic surveys (e.g., Czarnecki, Koppen, and Kingston) and the inclusion of diatoms in applied research efforts that set the groundwork for understanding post-glacial ecology, effects of Euroamerican settlement, impacts of climate, and the effects of acid precipitation. Important to these latter developments were the efforts of Dr. Herb Wright Jr., who invited several European diatomists (e.g., Florin, Battarbee, and Haworth) to work on paleoecological projects in and near Minnesota. Although not a diatomist *per se*, Wright's subsequent efforts to promote diatom research included the appointment of Platt Bradbury as a research associate and later John Kingston, Dick Brugam, and Brian Cumming. Students Sheri Fritz, Kate Laird, and Virginia Card completed diatom research for their doctoral degrees. These workers and others have left a legacy that continues to fuel several active labs in Minnesota that have used diatoms to develop water quality standards, assess and restore impaired waters, and understand the impacts of climate, management, and landuse change across the state.

Key words: science history, diatoms, Minnesota

Introduction

The state of Minnesota lies in the north-central continental United States, encompasses over 225,000 km² (12th largest state), and is home to nearly 5 million people (21st most populous state). Minnesota can be separated into seven major ecoregions, including: the Northern Minnesota Wetlands, Lake Agassiz Plain (Red River Valley), Northern Lakes and Forests, North Central Hardwood Forests, Northern Glaciated Plains, Western Corn Belt Plains, and the Paleozoic Plateau or Driftless Area (Omernik 1987). Most of the state was glaciated during the last (Wisconsin) Pleistocene glaciation. As a result of its glacial history, Minnesota has over 12,000 lakes (Wright 1989). The lakes are unevenly distributed in the state, with over 98% occurring in a NE-SW transect across the Northern Lakes and Forests, North Central Hardwood Forests, Northern Glaciated Plains, and Western Corn Belt Plains ecoregions. The lakes form a natural gradient along this transect: low pH, low salinity, low nutrient, and low alkalinity lakes in the Northern Lakes and Forests; higher pH, low salinity, intermediate nutrient levels, and higher alkalinity lakes in the North Central Hardwood Forests; and higher salinity, high alkalinity, high pH, and often elevated nutrients in the Northern Glaciated Plains, and Western

Corn Belt Plains ecoregions (Bright 1968). The Northern Minnesota Wetlands boast the Red Lake Peatlands, the largest US peat deposit outside of Alaska. Minnesota also has over 148,000 km of rivers and streams (Renwick and Eden 1999). Water in Minnesota follows three major drainages: Hudson Bay via the Red and Rainy rivers, Lake Superior via the St. Louis River and other North Shore streams, and the Gulf of Mexico via the Mississippi, Minnesota, St. Croix, and Missouri river basins (Tester 1995).

With such diversity of aquatic resources, Minnesota also boasts a rich diatom flora. Bright (1968) reports 350 species from 18 lakes, Koivo (1978) lists 346 taxa from 46 lakes, Pienkowski and Wujek (1987/88) report 102 taxa from the Red Lake Peatlands, Edlund (2009a) reports over 350 taxa from Lake St. Croix, and Florin (1970) reports about 230 taxa from Kirchner Marsh. Oligotrophic Lake Superior contains native populations of *Didymosphenia geminata* (Lyngbye) M. Schmidt in Schmidt et al. (1899: pl. 214, fig. 7–9), members of the *Cymbella cistula*-complex, diverse gomphonemoids, and several endemics (*Stephanodiscus superiorensis* Theriot & Stoermer (1984: 48), *Hannaea superiorensis* Bixby & Edlund in Bixby et al. (2005: 231). Lakes in northern Minnesota have rich *Aulacoseira* Thwaites (1848: 167), *Tabellaria* Ehrenberg ex F.T. Kützing (1844: 127), cyclotelloid, and soft-water floras (Bright 1968, Koppen 1975, Camburn and Kingston 1986, Edlund and Stoermer 1993, Camburn and Charles 2000). The southern and western parts of the state have more productive, saline, and alkaline lakes with diatom floras dominated by *Aulacoseira granulata* (Ehrenberg) Simonsen (1979: 58) and *A. ambigua* (Grunow) Simonsen (1979: 56), small *Stephanodiscus* Ehrenberg (1845: 72) and *Cyclostephanos* Round ex Theriot, Hakansson, Kociolek, Round & Stoermer (1987: 346) spp., benthic *Fragilaria* Lyngbye (1819: 182), and alkaliphilous *Anomoeoneis* Pfitzer (1871: 77), *Epithemia* Kützing (1844: 33), and *Rhopalodia* Müller (1895: 57) spp. A few lakes are saline and can be dominated by *Chaetoceras elmorei* Boyer (1914: 219).

The diatom flora of Minnesota has attracted researchers for over 150 years. Here we present a history of the study of diatoms in Minnesota.

Minnesota diatomists

The study of diatoms in Minnesota began before statehood was granted in 1858. In the 1840s and 1850s, the famous German microscopist, C.G. Ehrenberg, was actively corresponding with the American diatomist and microscopist Jacob Whitman Bailey, a professor in the Department of Chemistry, Mineralogy, and Geology at the United States Military Academy at West Point (Edgar 1977, Patrick 1986, Wynne 2003), and other American microscopists. Aware of the unique opportunities for sampling in the unexplored U.S. West, Ehrenberg coordinated with the director of the United States Naval Observatory, Lt. Matthew Fontaine Maury, who requested that the assistant surgeons at the frontier forts sample sediments and river water using standardized methods during 1852 and 1853 (Ehrenberg 1854). Samples collected at Fort Ripley along the Mississippi River in the central Territory of Minnesota were sent to Washington DC, where the Prussian Minister in Residence to the United States (ambassador), Mr. Friedrich von Gerolt, arranged for their transport to Ehrenberg (Ehrenberg 1854). The samples from Fort Ripley represented sediment samples and material from filtered river water collected monthly from June 1852 to May 1853 (Ehrenberg 1854). Ehrenberg analyzed the samples and published observations in his *Mikrogeologie* (1854), reporting 115 microscopic forms, including the first 73 diatoms (as Polygastern) collected in Minnesota. No new species were recognized, but Ehrenberg provided seasonal species richness data showing obvious spring and fall peaks in phytoplankton diversity on the Mississippi River.

Except for one small publication (Wyman 1883), nearly forty years passed before the next major report on the diatoms of Minnesota. The state geologist N.H. Winchell sent an interglacial peat from Blue Earth County to B.W. Thomas, who was better known for his early work on diatoms of Lake Michigan (Thomas and Chase 1886). Thomas collaborated with Prof. Hamilton L. Smith (who was trained by Bailey in his early years) to report 100 species of freshwater diatoms. One new species was recognized in the collection, *Navicula winchelliana* H.L. Smith in B.W. Thomas (1893: 296, 305–306), although its validity is questionable.

In 1895, the University of Minnesota hired its first female professor, Dr. Josephine Elizabeth Tilden (Hansen 1996), a phycologist well known for her studies of Pacific Ocean algae, cyanobacteria (Tilden 1910) and for the first phycology textbook (*Algae and its Life Relations*; Tilden 1935). Although diatoms were not Dr. Tilden's primary study organisms, her distribution of the exsiccata *American Algae* (several centuries were released while she was still an undergraduate!) included about 20 collections of Minnesota diatoms from the Minneapolis-St. Paul and the Duluth area (Tilden 1894–1909). Tilden partnered with the New York microscopist Arthur Meade Edwards to assist in her determinations. She also published several lists of algae, including diatoms from central and north-central Minnesota (Tilden 1894, 1895, 1896).

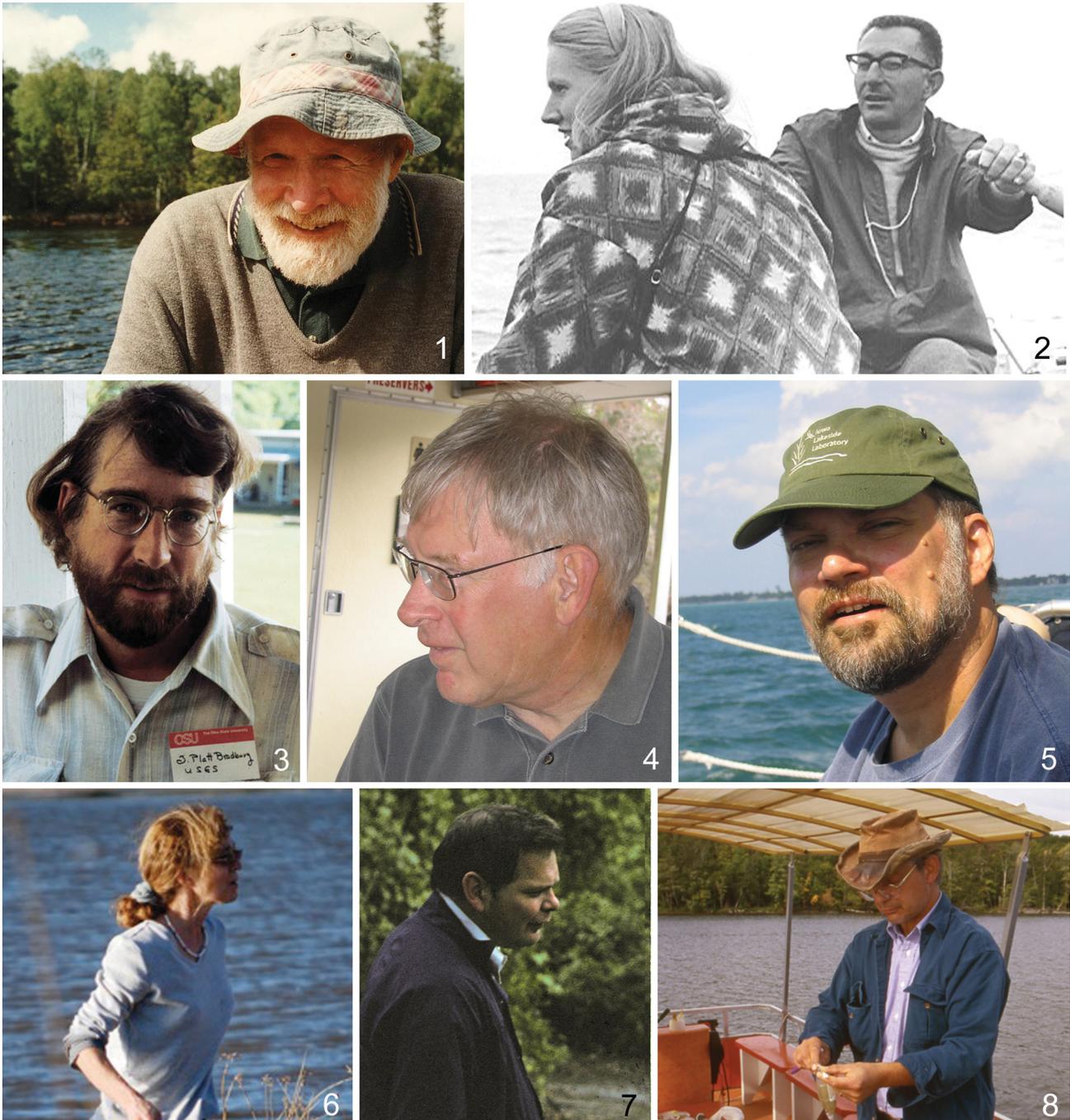
The first half of the 20th century saw few efforts to study the diatoms of Minnesota. Although other phycologists were working in the region, they rarely included diatoms in their research (Eddy 1930, Drouet 1954). A study of the St. Paul city water supply by Fanning (1901) had the first illustrated diatoms from Minnesota, ten common plankters. Survey work on the Mississippi River explored the ecology and increasing effects of pollution on this major commercial waterway (Galtsoff 1923–24, Wiebe 1928, Reinhard 1931). Other studies began to explore the ecological role of diatoms and algae in lakes and fisheries in the state (Nurnberger 1929, 1930; Reif 1940; Surber 1930, Surber and Olson 1937, Phillips 1969).

It was during the 1960s that the study of diatoms really took hold in Minnesota. Perhaps the most important person in that effort was Dr. Herb Wright, Jr. (Fig. 1), who was ironically never a diatomist. Wright led the formation of the Limnological Research Center (LRC) at the University of Minnesota, a research group that was an early leader in the field of paleolimnology. Through knowledge of European research, Wright had seen how diatoms were providing new lines of evidence in paleoecological studies on water-level changes in the Baltic region and post-glacial ecology, and he eventually invited European diatomists to work at the LRC. The first research associates were Maj-Britt Florin (1905–1993) from Sweden and Elizabeth Haworth (Fig. 2) from England. Rick Battarbee came from England in the 1980s to assist in the Northern Great Plains projects (Battarbee *et al.* 1984, Fritz *et al.* 1991, 1993). Florin focused her research efforts on the post-glacial record in Kirchner Marsh in central Minnesota, producing an illustrated flora and stratigraphy including the description of *Navicula kirchneriana* Florin (1970: 679). Based on the ecological preferences of the diatoms, Florin formulated with Wright an important model explaining the layer of plant detritus with terrestrial diatoms that is found at the bottom of many post-glacial lake stratigraphies (Florin and Wright 1969). Haworth's research looked at Holocene lake history of a site at the prairie border (Haworth 1972).

The influence of the European diatom researchers prompted other LRC associates and students to begin studying diatoms and other aquatic microfossils. Bob Bright (Fig. 2), who had spent time in Sweden studying under Maj-Britt Florin and Astrid Cleve-Euler, acknowledged the assistance of Florin and Haworth in his statewide survey of the relationship of diatoms to microhabitats and lake chemistry (Bright 1968). Donna Stark produced one of the first (and underappreciated) multiproxy paleolimnological studies of Elk Lake (Clearwater County), involving analysis of the modern distribution of aquatic plants, ostracods, molluscs, and chironomids at different depths, as well as their stratigraphic distribution in a transect of cores, all in the context of landscape history as recorded by pollen stratigraphy (Stark 1971, 1976). She was also involved with others in pollution history of three Minnesota lakes (Birks *et al.* 1976). Koivo (1978) studied the impacts of pollution on ecoregional patterns in plankton diversity across Minnesota.

In the late 1960s, Wright brought John Platt Bradbury (1936–2005; Fig. 3) to Minnesota as a research associate in the LRC. Bradbury's efforts targeted the impact of Euroamerican settlement on lakes using both paired lake studies and regional assessments. His classic study of Shagawa and Burntside lakes near Ely showed the differing impacts of cultural activities on two contrasting lakes (Bradbury 1978), and his synthesis of sediment records from nine lakes across Minnesota and South Dakota identified common patterns of changes in the diatom communities as a result of land clearance, erosion, and settlement around the lakes (Bradbury 1975). Bradbury left the LRC for a position with the U.S. Geological Survey in the mid-1970s but continued his study on the varved sediment record in Minnesota's Elk Lake (see below). One of Platt's lasting contributions to the broader community of diatomists was the first North American Diatom Symposium (called the "*First Symposium. Ecology of Freshwater Diatoms*"), that he co-organized with Ryan Drum in

1970 and held at the Cedar Creek Natural History Area (Bradbury 1973). The North American Diatom Symposium (NADS) has returned twice to Minnesota, with the 10th NADS hosted by Dave Czarnecki at Lake Itasca and the 16th NADS hosted by John Kingston near Ely.



FIGURES 1–8. Minnesota diatomists. Fig. 1: Herb Wright, Jr. in the Boundary Waters Canoe Area Wilderness, 2006 (photo Brigitt Amman). Fig. 2: Elizabeth Haworth and Bob Bright (photo Roger Woo). Fig. 3: J. Platt Bradbury, 1974 North American Diatom Symposium (NADS), Hocking Hills, Ohio (photo E.F. Stoermer). Fig. 4: Dick Brugam, 2005 NADS, Mobile, Alabama (photo M. Edlund). Fig. 5: John Kingston, 2003 NADS, Isle Morada, Florida (photo M. Edlund). Fig. 6: Sheri Fritz, Nebraska Sand Hills (photo J. Schmierer). Fig. 7: John Koppen, 1976 NADS, Philadelphia, Pennsylvania (photo E.F. Stoermer). Fig. 8: David Czarnecki, 1997 NADS, Douglas Lake, Michigan (photo M. Edlund).

Wright's next diatomist incumbent at LRC was Richard Brugam (Fig. 4). Brugam worked on diatom stratigraphy from several Holocene lake and bog records (Brugam 1980, Brugam *et al.* 1988, Brugam and Swain 2000). He also made early inroads into quantitative environmental reconstruction through the use of indices (Brugam 1979, Brugam and Patterson 1983) and surface-sediment analogues (Brugam 1983, 1993).

John Kingston (1949–2004; Fig. 5) came to LRC in the early 1980s as a post-doctoral research associate. Kingston's research focused on the Red Lake peatlands of northern Minnesota and whether diatoms could be used as paleoecological indicators. Kingston found poor preservation of diatoms in the silica-poor bogs but published an ecological study of the peatland diatom assemblages (Kingston 1982). When diatoms became increasingly important in paleoecological studies, Kingston left for Duluth, where he headed up the PIRLA project (Paleolimnological Investigations of Recent Lake Acidification; Kingston *et al.* 1990) to determine the extent and severity of recent lake acidification across the United States. Several of the study sites were located in Minnesota and resulted in taxonomic treatments of the diatom floras (Camburn and Kingston 1986, Camburn and Charles 2000; the latter included the description of *Pinnularia microstauron* var. *lunicus* Camburn & Charles (2000: 28) from Dunnigan Lake). With multiple labs working on PIRLA, taxonomic consistency was a key element of their quality control, and many Minnesota diatoms were reported in the "*PIRLA Iconograph*" (Camburn *et al.* 1984–1986). Kingston left to work in Canada and Colorado but returned to Minnesota in 1999 to head up the Ely Field Station for NRRRI's Center for Water and the Environment where he established an active lab with multiple diatomists. Kingston's lab (now headed by Euan Reavie) continued work on Minnesota lakes and diatoms (Kingston 2001, Reavie and Baratono 2007) and helped initiate new efforts to use diatoms as ecological indicators in the Great Lakes (see below) and Great Rivers (Reavie *et al.* 2010), before John's untimely passing in 2004.

Several of Wright's graduate students, including Sheri Fritz (Fig. 6), Dan Engstrom, and Virginia Card, also used diatoms as paleo-indicators in their research. They continue to build on the study of diatoms in Minnesota. Fritz worked on Great Plains drought records (Fritz *et al.* 1991, 1993) and also trained both students and postdocs as a research associate at LRC (Laird *et al.* 1998). Fritz left Minnesota for Lehigh University and eventually the University of Nebraska; however, she and her graduate students and post-docs continued to work in the region (Saros *et al.* 2000, Ramstack *et al.* 2003, 2004). Jeannine-Marie St. Jacques, a student of Brian Cumming, who was a post-doc with Sheri Fritz, analyzed diatoms from a short core of varved sediments from Lake Mina in western Minnesota (St. Jacques *et al.* 2009). Engstrom initially partnered with John Kingston to work on Harvey's Lake in Vermont (Engstrom *et al.* 1985). He later became head of the St. Croix Watershed Research Station, where he established an active diatom group (Mark Edlund, Joy Ramstack Hobbs, Will Hobbs), where training of students continues and whose work has been crucial in setting state water quality standards (Ramstack *et al.* 2004, Heiskary and Wilson 2008) and remediation policies (Edlund *et al.* 2009b). Virginia Card worked on varved sediment records from central Minnesota (Tracey *et al.* 1996, Card 1997), and took a position at Metropolitan State University in St. Paul where diatoms are well-integrated into her teaching and research agenda.

Herb Wright's vision to bring the study of diatoms to Minnesota has shaped many research programs in the state. Several diatomists, however, came independently to work in Minnesota on taxonomic, systematic, ecological, and floristic diatom studies. John Koppen (Fig. 7) used collections from throughout Minnesota for his monographic treatment of the genus *Tabellaria*, in which he studied both the ecology and taxonomy of the group, identifying morphological "strains" whose names are still widely used (Koppen 1975, 1978). Pienkowski and Wujek (1987/88) reported 102 diatom taxa from sites in the Red Lake Peatlands. Dave Czarnecki (1947–2006; Fig. 8) taught phycology for many years at the Lake Itasca Biological Station, where he and his students used the area diatom flora as culture sources (Czarnecki 1987; Czarnecki and Ross 1987/1988; Czarnecki 1994) and explored the diatom assemblages in specialized habitats in the region (Ngô *et al.* 1987, Edlund 1994, Czarnecki 1995). Czarnecki sadly passed away in 2006, and his diatom cultures were transferred to the UTEX culture collection (<http://web.biosci.utexas.edu/utex/>). Matthew Julius replaced Keith Knutson at St. Cloud State University and runs an active laboratory working on systematics, toxicology, and functional ecology of diatoms.

Several regions or lakes in Minnesota have been the focal points of research using diatoms and deserve special mention. Perhaps the best-studied lake in Minnesota is Elk Lake in Itasca State Park (Clearwater County). The deep hole in Elk Lake preserves an 11,000 year varved record that has attracted the attention of paleolimnologists and climatologists for four decades. From Stark's (1971, 1976) initial multiproxy study on the lake to the synthesis by Bradbury and Dean (1993), the diatoms have played a critical role for understanding lake response to climate change. Bradbury's "climatic-limnological model" of diatom succession (Bradbury 1988) was an early example of marrying neo- and paleolimnological approaches, and it is still often cited in the interpretation of recent climatic-change records in temperate lakes (Bradbury and Dieterich-Rurup 1993, Bradbury *et al.* 2002).

Along Minnesota's northeastern border lies the world's largest freshwater lake (by surface area), Lake Superior. The nearshore diatom flora of Lake Superior has been increasingly used for study of systematic, ecological, and environmental-assessment problems. Early diatom work dealt with survey and fisheries management (Smith and Moyle 1944). The partnering of efforts by Ted Olson and Ted Odlaug, head of the University of Minnesota's School of Public Health and the University of Minnesota-Duluth's Biology Department, respectively, led to the study of the ecology of Lake Superior periphyton and its response to nutrient enrichment (Fox *et al.* 1967, 1969, Nelson *et al.* 1973). Other workers have studied the diatoms of Lake Superior to better understand their taxonomic and systematic relationships (Stoermer *et al.* 1986), including the description of several taxa (*Gomphoneis geitleri* Kociolek & Stoermer (1991: 1570–1571); *Hannaea superiorenensis* Bixby *et al.* 2005). More recently, diatom assemblages in nearshore and wetland habitats in the Great Lakes including Lake Superior are being used to assess water quality and coastal conditions (Reavie 2007, Reavie *et al.* 2006, 2008, Kireta *et al.* 2007, Sgro *et al.* 2007).

The large river systems in Minnesota, especially the Upper Mississippi River and its tributaries (Minnesota and St. Croix rivers), have experienced dramatic changes in hydrology, morphology, navigation, and nutrient and sediment loading since Euroamerican settlement. As a result, much research effort has been directed at their algae, phytoplankton, and environmental histories. The earliest work documented water quality degradation as a burgeoning population and industrial base used the rivers as open sewers (Galtsoff 1923–24, Wiebe 1928, Reinhard 1931). Later work concentrated on algal seasonality and ecology and the response of algae to nutrient additions (Kaddatz and Knutson 1980, Kromer-Baker and Baker 1981, Huff 1986, Luttenton *et al.* 1986, Kutka and Richards 1997). Large federal projects, such as the National Water Quality Network, have included the large Minnesota rivers in their sampling design. Diatoms are a major player in the phytoplankton biomass of rivers, and their abundance and diversity have been reported in the major project syntheses (e.g., Williams and Scott 1962, Williams 1964, 1972). Most recently has been large scale sampling of US Great Rivers to develop algal and diatom metrics of ecosystem health (Reavie *et al.* 2010, Kireta *et al.* 2012, Sgro *et al.* 2012).

Perhaps the most interesting application of diatom analysis on Minnesota's large rivers has been for historical environmental reconstructions. Because of delta formation at the mouth of Wisconsin's Chippewa River as it enters the Mississippi River, Lake Pepin was formed. Pepin originally extended far up the Mississippi River above the mouth of the St. Croix River. The delta at the head of Lake Pepin eventually prograded across the mouth of the St. Croix River, forming Lake St. Croix. The Lake Pepin and Lake St. Croix sections of the Mississippi drainage system function as lakes with short residence times, and they have preserved unique lacustrine sediment record of the river and watershed history for over 10000 years. Using ecological preferences, diatom-inferred phosphorus reconstructions, and whole-lake mass balance techniques, Edlund *et al.* (2009a) and Engstrom *et al.* (2009) showed that both rivers had experienced dramatic ecological shifts to planktonic dominance, increases in total phosphorus levels, and increased phosphorus loading. These changes were most notable after World War II in response to a growing population and increased loading from point and non-point sources. Sedimentation histories showed differences between the two rivers; infilling rates in Lake Pepin continue to increase whereas sedimentation in Lake St. Croix peaked in the 1960s (Engstrom *et al.* 2009, Triplett *et al.* 2009). Results from these studies have been used to develop nutrient and sedimentation targets for remediation after both rivers were shown to be impaired because of nutrients and the

Mississippi also because of turbidity (Edlund *et al.* 2009b). Lastly, these results show a clear temporal linkage between environmental degradation in the Upper Mississippi Basin and coastal eutrophication and hypoxia in the Gulf of Mexico (Edlund *et al.* 2009a).

After 150 years of diatom study in Minnesota, opportunities to use diatom analysis to address environmental problems continue to dominate the research arena. With its wealth and diversity of aquatic resources that are threatened by development, the introduction of exotic species, land-use, recreation, eutrophication, atmospheric deposition, and climate change, Minnesota boasts a strong foundation of diatom-based research and an unusual abundance of active laboratories to help address these issues, guaranteeing that the study of diatoms will continue in this region for many years.

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