Climatic and Anthropogenic Influences on Aquatic Ecosystems in the Valley of the Great Lakes, Mongolia

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Abstract

Climate warming and major land use changes have profoundly affected the Mongolian landscape in the past several decades. As in many arid and semi-arid regions, water resources are critically important for ecological, social, and economic viability. In Mongolia, traditional semi-nomadic pastoralism contributes substantially to the national economy as well as to individual subsistence and depends on limited freshwater resources to provide for grazing herds and human needs. Yet, because of substantial variability across this immense region, its remoteness, and recent political transitions, little work has been done to monitor water quality or to set baseline standards against which to measure future changes. Compounding the problem is a lack of well-resolved paleo-ecological and paleo-climatological work. These data are necessary to provide a foundation for understanding the natural variability in the aquatic systems of the region, especially with recent changes in climate and land use. This work is a contribution to developing these records by first, developing diatom-based inference models for total phosphorus and salinity, and second, applying the models to investigate lacustrine sediment records of past changes.

The diatom-based inference models were based on a survey of the water chemistry, physical characteristics, and diatom flora of 64 lakes in western Mongolia. The region had a diverse diatom flora with over 300 species, nearly 100 of which had not been previously reported from Mongolia, from lakes ranging from fresh to hyper-saline. The many isolated lake basins provided unique ecosystems where multiple unique communities, novel species distributions, and new and endemic flora were found. Three of these new species are described here in a careful examination of the genus *Cyclotella* in western Mongolia. Canonical correspondence analysis (CCA) was used to identify four variables (specific conductivity, total phosphorus, bicarbonate, and lake morphology) that were significantly related to the distribution of diatoms; predictive models were developed for specific conductivity and total phosphorus using weighted averaging regression and calibration methods.

The application of these models to dated lake sediment cores, along with interpretations of other geochemical and sediment characteristics, was then used to develop records of variability in lake salinity and nutrient flux. The interpretation of diatom and sedimentary records demonstrated increases in nutrient fluxes to the lakes related to climate warming and major changes in land-use over the last 20 years. Diatom-inferred lake salinity was correlated with changes in temperature over the past 2000 years, as inferred from tree-ring records, demonstrating a positive relationship between increased warming and increased lake salinity in recent geologic history. Changes in warm-season temperature, as inferred from tree-rings, in the most recent decades were less-well correlated with inferred changes in salinity than over most of the 2000 year record. However, instrumental records of winter temperature were well correlated with recent shifts in inferred salinity, perhaps suggesting recent changes in climate that are unique from those over the past several thousand years.

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Introduction

Background

For thousands of years Mongolia has maintained a subsistence lifestyle based on nomadic herding, a tradition which has been identified by the Mongolian government in an initiative to preserve national cultural heritage (Ministry for Nature and the Environment 1996). In recent surveys taken in western and central Mongolia, herders identified water quality and availability as their most pressing concern (Sternberg 2008). Primary concerns included both failure of human infrastructure, such as lack of well maintenance, and environmental changes, including the drying up and salinization of water bodies. Since 2002, more than 3000 lakes and streams have been reported to run dry across the country due to a combination of climate and land-use changes; this concern is especially acute in the western regions of the country where 80% of surface water bodies are already saline (Batima 2006).

The recent several decades have shown a great deal of change and variability in climate in arid Central Asia. Surface air temperatures in the region have been rising annually, with a total increase of 1.8º C in mean annual temperature since 1940. Warming is more pronounced in winter, with an increase in mean seasonal temperature of 3.6 º C over the same time period (Batima 2006). As winter temperatures rise, the Siberian High pressure system is weakening. This weakening will likely lead to increased snowfall over the region (Aizen et al. 2001), as has previously been predicted in global climate models (Giorgi et al. 2001). While summer precipitation has not decreased significantly across the region, increased evapo-transpiration due to warming has led to recent increases in drought conditions (Dai et al. 2004) and may lead to concerns about future freshwater availability.

Throughout recorded history, grazing on the steppe has been regulated by a variety of traditional religious and political codes and institutions which formalized and managed migration to seasonal pastures and kept limits on the numbers and variety of animals in a given herd (Germeraad and Enebisch 1996). During the Soviet era, for example, the total livestock population in Mongolia varied by less than 5 million animals (Sneath 1999). With the end of the Soviet era in 1991, communist government controls were removed and a free-market economy was established. In the eight years following the transition from command to market economy, the livestock population increased by 10-15 million animals. While a series of natural disasters led to a decline in the animal population between 1999 and 2003, the numbers quickly rebounded in 2004 and have continued to rise in the years since (Bold 1998; World Bank 2003; FAO 2007). Today eighty percent of land in Mongolia is dedicated to pastoral use and the pastoral economy employs nearly 50% of the nation's population (Batima 2006). In the current free-market economy, herders have great incentives to increase herd sizes, with the greatest increases occurring in the population of cashmere goats (Mearns 2004). As livestock numbers have increased, the mobility of herders and livestock has decreased, often focusing large herds in small areas, and concentrating the increased impacts of heavy grazing (Fernández-Giménez and Batbuyan 2004; Mearns 2004).

These recent and rapid changes in climate and land-use have led to increased concerns over the future sustainability of the terrestrial and aquatic ecosystems on the steppe, as well as the viability of the livelihoods that depend on the region's natural resources. Understanding the long-term history of these ecosystems, their natural variability, and the relationship between climate, land-use, human impacts, and ecosystem health is becoming increasingly important to the management of the unique natural resources in Mongolia.

History of paleo-climatic and paleo-ecological research in Mongolia

Several investigations of long term temperature and moisture balance changes have been conducted in Mongolia. Past research has, however, focused mainly on very broad time scales; most studies have multi-centennial scale resolution at best. Dorofeyuk and Tarasov (1998) used pollen assemblages and classification of diatom assemblages into salinity groups as established by Kolbe (1927), to create a Holocene climate history for three lakes in northern Mongolia. They found marked differences in the response of Gun Lake, in the south, from Hovsgol Lake and Dood Lake, in the north. Gun Lake was found to be at its maximum extent from 7000-7500 years before present and had a shallowing phase from 3000-4000 y.b.p. before rising again and stabilizing around 2000-2500 years ago. The two northern lakes were high during the Pleistocene but shallowed between 10,000 and 11,200 years ago and remained at a low stand through the Mid-Holocene (Dorofeyuk and Tarasov 1998). A series of pollen records from lakes in the northern and central regions showed changes in plant communities that suggested a drier than present climate in the Late Glacial and Early Holocene, and more humid than present climate through the Mid-Holocene, persisting until about 4000 years before present (Gunin et al. 1999). Records based on pollen data, changes in lithology (Fowell et al. 2003) and changes in diatom species and their ecological preferences in North America (Soninkhishig et al. 2001) have been applied to interpret the lake level history of

Lake Telmen, in west central Mongolia. These records indicated an arid period through most of the Mid-Holocene, becoming more humid at around 4500 y.b.p. A humid climate, relative to the Mid-Holocene, is recorded through most of the Late Holocene with several arid excursions. These records do not completely agree with the pollen records of Gunin et al. (1999) on the major arid and humid intervals of the Holocene. In fact, in twelve records of moisture availability from western and central Mongolia, which were derived from lake level history based on sediment lithology, geomorphologic features, pollen and diatom species changes preserved in lake sediments, there is much disagreement on the timing and extent of moisture availability over most of the Holocene. Of the records available that cover the Mid-Holocene (5000-7000 y.b.p.), five records indicate higher than average moisture availability (Gunin et al. 1999; Tarasov et al. 1996; Lehmkuhl and Lang 2001; Dorofeyuk and Tarasov 1998) while four record an arid period (Dorofeyuk and Tarasov 1998; Fowell et al. 2003; Soninkhishig et al. 2001; Tarasov et al. 1996). At 2000 y.b.p., four lakes indicate arid conditions (Tarasov et al. 1996; Dorofeyuk and Tarasov 1998), while three others have records indicating a surplus of moisture (Tarasov et al. 1996; Fowell et al. 2001; Soninkhishig et al. 2001). The result has been a complex picture of the climate history of the region.

While reconstructing broad climatic changes on Holocene time scales and longer is important to an overall understanding of the climate system, it does little to put recent, decadal scale changes into context. Research has also been done to refine climate changes over shorter time scales in the last several thousand years. Several tree ring chronologies have been published from Mongolia, largely from the central and northeastern parts of the country. Many of these records come from temperature sensitive regions, where the width of the growth ring reflects the mean air temperature during the growing season. These chronologies have established a good understanding of temperature variability and change in the recent past, and agree on warm periods in the 13th, 15th, and 18th centuries. Tree ring records also demonstrate that inter-annual temperature variation in the most recent several decades is within natural variation over the last several thousand years, however, reconstructed temperatures are the warmest in the record (Jacoby et al. 1996; D'Arrigo et al. 1999; D'Arrigo et al. 2001). Though temperature records are important, arguably more important to understanding the impact climate change will have on human livelihoods is an understanding of moisture availability in the desert and steppe. At least two studies have focused on resolving shorter-term (decadal to centennial) fluctuations in moisture balance with changing temperature, one from Lake Telmen, in west-central Mongolia (Fowell et al. 2003), and another using a moisture-sensitive tree-ring chronology from the Selenge River basin in central Mongolia (Davi et al. 2006). Both of these studies, however, are limited in their regional scope, differ in resolution, and are contradictory to one another over some intervals. For example, the sediment and pollen-based aridity record from Lake Telmen found both the 'Medieval Warm Period' and the 'Little Ice Age' (LIA) to be more humid than average (Fowell et al. 2003), while the tree-ring chronology from a nearby region found that some periods within the LIA were comparatively arid (Davi et al. 2006).

Very little previous work has been done to assess the water quality in the region. Some attention has been paid to the impact of mining and industrial development on rivers with potential as recreational fisheries (Soninkhishig 1998; Stubblefield et al. 2005; Kelderman and Batima 2006), but the overall health of aquatic systems is largely unknown.

Diatoms as proxies

While many possible proxies can be used to infer past environmental conditions from lake sediment records, diatoms are well suited for answering the particular questions involved in this study. A variety of limnological parameters are known to act as limiting factors for certain diatom species, including pH, lake depth, salinity, and nutrient concentration (Stoermer and Smol 1999). In arid and semi-arid parts of the world, a major control on diatom distributions is the hydrologic balance. These changes are manifested primarily as changes in lake level, which re-shapes the size and availability of unique habitat niches, and changes in the type and strength of the ionic concentration of the water (Gasse 2002). Studies reconstructing moisture balance and climate change through diatom-inferred salinity have been successful in many areas, including other continental, semi-arid environments such as the Great Plains of North America (Fritz et al. 1993) and the African Sahel (Gasse 2002).

Measures of past change in nutrient concentration can be more difficult to estimate; seasonal variability in phosphorus, diatom ecology, and the varied response of diatoms to changing phosphorus concentrations in combination with other variables can make the estimation of optima and tolerances for phosphorus difficult (Anderson et al. 1993; Hall et al. 1997; Sayer 2001; Bradshaw and Anderson 2001). Despite these issues, diatom-based inferences of phosphorus concentrations have matched reasonably well with measured data, especially in large lakes where planktonic diatom species dominate (e.g. Bennion et al. 1996; Lotter 1998). Phosphorus reconstructions from shallow lakes with predominantly benthic taxa can be somewhat less reliable (Sayer 2001). In the diatom-inferred records developed here, the diatom responses to changing nutrient conditions were somewhat more ambiguous than those for salinity, particularly in relatively shallow lakes. Due to this ambiguity, and because phosphorous was less significant than salinity in explaining the distribution of modern diatoms in the calibration set, additional measures including sediment phosphorus, biogenic silica, organic matter content, and the broader diatom community structure were also used in chapter three as additional or independent measures of nutrient concentrations in the lakes over time.

Lakes in the calibration set presented here were sampled specifically for a salinity gradient, and found later to have a significant nutrient gradient as well. Developing inferences based on the response of diatoms to a secondary gradient can result in complications with covariance (Anderson 2000). Using variance partitioning, the significance of each variable alone and in combination with other variables was assessed and the confounding interaction of multiple variables could be more completely understood (Lotter 1998; Hall et al. 1999). While complicated, transfer functions re-constructing more than one variable from the same diatom calibration set have proven informative in other studies (Hall et al. 1999; King et al. 2000; Reavie and Smol 2001; Ramstack et al. 2003).

In Mongolia, researchers have been studying the diatom flora for over 100 years. The first published investigation of diatom distribution was a report on species found in Lake Hövsgöl by Dorogostaïsky in 1904 (Edlund et al. 2001). Diatom studies by Russian, Mongolian and international scientists have proceeded through the last century (e.g. Skvortzow 1937; Morales 2003; Edlund et al. 2003); however, work has been largely focused on reports of occurrences and distribution with little ecological focus. In recent decades, interest has been building in Mongolia and surrounding regions to use diatoms in paleo-climatological and paleo-ecological assessments (Edlund et al. 2001; Soninkhishig et al. 2001; Westover 2006).

Chapter summaries

The task of developing a well-calibrated inference model, using this model to develop temporally and spatially resolved paleo-climatic and paleo-ecological records across all of Mongolia and neighboring arid regions, applying these records to improve existing climate projections, and setting in motion the development of water quality monitoring based on known baseline conditions for the wide variety of lakes in the region, not to mention the local and governmental will required to put all these pieces into place, is well more than one person's work. I hope, however, the tools developed here as well as the findings and the new questions raised, are a start to continued research into these important issues.

Chapter one details a survey of the diatom flora from 64 lakes across western

Mongolia. The diatoms in each lake were linked with water chemistry to develop a regional calibration set associating diatom communities with their preferred environmental conditions. The calibration demonstrated that diatom communities varied most distinctly in relation to changes in overall salinity (measured as specific conductivity) among the lakes; total phosphorus, bicarbonate concentration and lake morphology were also significant gradients in the calibration set. These relationships were used to establish species optima and tolerances for both specific conductivity and total phosphorus and to develop a weighted averaging model to infer salinity and total phosphorus using diatom assemblages in dated lake sediment cores. This chapter is in press in The Journal of Paleoliminology, with co-authors Jim Almendinger (Saint Croix Watershed Research Station, Mark Edlund (Saint Croix Watershed Research Station), and N. Soninkhishig (National University of Mongolia). The water chemistry data were collected and analyzed primarily by Jim Almendinger. N. Soninkhishig provided logistical planning and field support for the survey, and Mark Edlund was instrumental in the initial planning of the calibration set development, as well as in the identification of rare species and overall editing and review.

Even with over a century of diatom research in the region, relatively little of the diatom flora of Mongolia has been described. The many isolated basins offer a wide variety of habitat and opportunities for the development of unique communities and potentially endemic flora. Chapter two describes the distribution of one group of diatoms, broadly included in the genus *Cyclotella*. Typically a diverse and abundant group which often plays a major role in the reconstruction of salinity in paleolimnological records from arid regions (Carvahalo et al. 1995), the distribution of the group in the lakes of western Mongolia was strikingly limited and included at least three species new to science. Provisional descriptions of these three species, *Puncticulata khyargusiana* prov. nom., *Cyclotella uuregensis* prov. nom., and *Cyclotella buyanysogii* prov. nom. are included in this chapter and will be formally described and effectively published in a peer-reviewed journal. These diatoms represent a small number of the new species waiting to be described from the unique saline environments of this region. Aside from documenting the biodiversity of aquatic resources in the region, accurately identifying and describing the diatom communities in this part of the world is critical to the future work linking and expanding this work with datasets from other regions. This chapter will be submitted for publication with co-authors Mark Edlund (Saint Croix Watershed Research Station) and Matthew Julius (St. Cloud State University). Both co-authors were instrumental in identifying and defining the unique characteristics of these diatoms as compared with other members of the genus.

The relatively recent problem of eutrophication in regional lakes is addressed in chapter three. During the lake surveys undertaken for development of the calibration set, it was apparent that many of the lakes in western Mongolia were highly eutrophic. In the absence of any monitoring data, the extent, rate, and timing of eutrophication in the lakes was difficult to assess. If the lakes had been similarly eutrophic over most of recent history, there would be less reason for immediate concern. However, major changes in the grazing habits of pastoralists have taken place since the privatization of the economy after the collapse of the communist government in 1991. If these changes were the source of the nutrient enrichment, water quality and aquatic ecosystem health may have deteriorated rapidly over the last decade. Such rapid changes would indicate immediate challenges that need to be addressed in order to preserve these lakes and wetlands. Records of basic productivity proxies, including diatom-inferred total phosphorus, sediment phosphorus, and biogenic silica, demonstrated that productivity in most lakes has varied over time, and typically increased slightly during warm intervals. However, recent increases in indicators of productivity, including sediment phosphorus, biogenic silica, and the proportion of planktonic diatom flora, are much larger than the prior increases in inferred productivity with warming temperatures. Variance partitioning between changes in diatom community structure, instrumental records of climate, and historical records of livestock population demonstrated that the major changes in the diatom communities, indicative of increasingly eutrophic conditions over the last two decades, were related primarily to a combination of winter warming and increased livestock population. This chapter is intended for publication with co-authors Charles Umbanhowar (St. Olaf College), Jim Almendinger (Saint Croix Watershed Research Station), Mark Edlund (Saint Croix Watershed Research Station), and N. Soninkhishig (National University of Mongolia). Charles Umbanhowar processed sediment to obtain charcoal for ^{14}C dating and collected sediment phosphorus and biogenic silica data. Water chemistry data defining the modern trophic status of the lakes was collected and analyzed by Jim Almendinger. N. Soninkhishig and Mark Edlund provided support in planning the project, collecting background data, and reviewing and editing the chapter.

In the final chapter, the diatom-based weighted-averaging model for conductivity was applied to six dated sediment cores. Increases in salinity are a major concern for water availability and quality (Sternberg 2008) and ecosystem function (Williams 2002) in arid regions of Asia. This chapter examines changes in moisture balance across the region over the past 2000 years, and relates the changes to inferred and measured changes in regional temperature from both published tree-ring records (D’Arrigo et al. 2001) and instrumental data (KNMI 2007). These diatom-inferred records, along with sediment characterization conducted in cooperation with Charles Umbanhowar, demonstrated increased salinity during prolonged warm periods. While the increases in diatom-inferred salinity over most of the 2000-year record are moderately well correlated with changes in growing season temperature, as inferred from the published tree-ring chronology, recent diatom community changes are poorly correlated with the tree-ring record, likely due to the links with winter warming and land-use changes identified in chapter three. This chapter is intended for publication with co-authors Charles Umbanhowar (St. Olaf College), Mark Edlund (Saint Croix Watershed Research Station), and N. Soninkhishig (National University of Mongolia). Charles processed sediment to obtain charcoal for ^{14}C dating and led sampling efforts to characterize the magnetic properties and grain size of the sediments. N. Soninkhishig and Mark Edlund provided support in planning the project, collecting background data, and reviewing and editing the chapter.

Chapter 1

Diatoms as indicators of water quality in Western Mongolian lakes: a 54-site calibration set

Abstract

Mongolia is an arid land with limited freshwater availability. Recent changes in climate as well as changes in livestock management in the post-Soviet era may threaten the quality and availability of these freshwater resources and emphasize the need to characterize current conditions relative to a long-term baseline. Because diatoms are responsive to changes in water chemistry and are commonly preserved in lake sediments, they can be used as indicators of both present and past water quality. To these ends, we have developed a diatom-based calibration set and quantitative inference models for the region. Physical and chemical factors and modern diatom communities were sampled at 54 sites in western Mongolia in the Altai and Khangai mountains and the Valley of the Great Lakes. Canonical correspondence analysis (CCA) demonstrated that both salinity and total phosphorus accounted for statistically significant fractions of the variation in 151 diatom taxa across the 54 sampled sites. Diatom-based inference models were developed with weighted averaging (WA) techniques and showed strong predictive capabilities and low prediction errors for salinity and total phosphorus. These models are now available to help identify and interpret historical and future disturbances to this sensitive and globally important eco-region.

Introduction

The Valley of the Great Lakes in Western Mongolia is a hydrologically closed tectonic depression in an ecologically significant region of Central Asia. The region includes several areas designated "Strictly Protected" by the Mongolian government and is registered on the UNESCO Biosphere Reserve and World Heritage List. The Mongolian steppe is one of the last refuges of several threatened and endangered species, including the argali sheep, the gobi bear, the Mongolian wild horse, and several bird species (Ministry for Nature and the Environment 1997). For thousands of years Mongolia has maintained a subsistence lifestyle based on nomadic herding, a tradition which has been identified by the Mongolian government in an initiative to preserve national cultural heritage (Ministry for Nature and the Environment 1996). The quality of habitat and environment for Mongolians and their animal herds, as well as at-risk wild species, may be under threat from rapid climate change and changes in the use of freshwater resources. Understanding the vulnerability of this unique ecoregion to these changes is critical for future conservation efforts.

The mountains and grasslands of western Mongolia lie at the transition between sub-arctic ecosystems to the north and the arid desert regions to the south. Winter warming over the last several decades has been greatest in the mid-latitudes of the northern hemisphere, especially at high elevation sites (Houghton et al. 2001). Recent and continuing changes in global climate also include modifications to the hydrologic cycle; semi-arid regions are expected to experience increasing drought with increases in short, intense storms (Dai et al. 2004; Solomon et al. 2007). Rising air temperatures are expected to increase evaporative rates, leading to drier conditions even where precipitation is not dramatically decreased (Dai et al. 2004).

Changes in the climate system are already apparent in Mongolia. Surface air temperatures in the region have been rising on an annual basis, with a total increase of 1.8° C in mean annual temperature since 1940 (Batima 2006), more than twice that of the global average (Houghton et al. 2001). Precipitation has not declined significantly in most regions; however, a persistent drought in 1999-2002 has raised concerns about the future of pasturelands. At present, nearly 20% of surface water bodies in Mongolia are permanently saline, with a larger portion of these in the western and southern regions (Batbold et al. 2004). In western Mongolia, where 80% of surface waters are already saline, more than 3000 water bodies have gone dry in recent decades due to a combination of climate and land use changes (Batima 2006) and approximately 2000 wells have ceased to be maintained since the 1991 collapse of the Soviet government (Batbold et al. 2004).

As the availability of fresh water decreases, other potential threats to the area include large increases in the number of grazing animals due to privatization of the herding economy. Since the end of Soviet authority in 1991, traditional nomadic herders have seen large incentives to increase their number of livestock, particularly numbers of cashmere goat (Mearns 2004). The larger number of animals and humans utilizing the scarce freshwater resources may be impacting the nutrient load in these systems and creating a deleterious situation for both wildlife and local herders. Eutrophication, commonly caused by excessive inputs of phosphorus and other nutrients from human and animal waste and agricultural practices, can lead to negative impacts such as low oxygen, algal blooms, decreased light availability, and decreased biodiversity (Bennett et al. 2001).

Diatom records have been successfully used as indicators of lake salinity and trophic status in a variety of modern and paleo-climatological and paleo-ecological studies (Stoermer and Smol 1999). Here we have linked water chemistry to diatom assemblages and found that salinity, total phosphorus, lake morphology, and bicarbonate had significant influence on the composition of diatom communities in Mongolian lakes. We used this understanding to construct transfer functions to quantitatively infer lake-water salinity and total phosphorus from these diatom assemblages, thereby providing a tool that can be used to assess the magnitude and timing of regional changes in climatic moisture and nutrient loading to regional lakes.

Study area

The Valley of the Great Lakes lies in the far west of Mongolia, bounded by the Altai Mountains to the west, the Khangai Mountains to the east, and the Gobi Desert to the south (Figure 1-1). The region is a structurally complex and tectonically active zone underlain by various Paleozoic and older arc complexes and continental fragments. Large compressional basins, such as the Valley of the Great Lakes, were formed during terrane accretion in the late Tertiary (Sladen and Traynor 2000).
The Great Lakes region is part of the endorheic Central Asian Basin and includes several smaller closed drainage basins with lakes ranging from fresh to hypersaline (Dulmaa 1979). Many of the large terminal basins in the valley are believed to be the

remnants of large Tertiary or Quaternary paleo-lakes (Grunert et al. 2000). There are additionally numerous large and small permanent and ephemeral ponds, playa lakes, floodplain lakes, and dune-blocked lakes.

There is a strong gradient of annual precipitation in the region, as well as several ecosystem boundaries, making the region highly responsive to changes in effective moisture. Most of the country experiences annual temperature fluctuations in the range of 50-55° C, with the minimum and maximum temperatures recorded in the country separated by nearly 100° Celsius. Winters are cold and dry, controlled by the development of the strong Siberian high pressure system during the fall and early winter. Most precipitation in the region falls in summer, the result of local convective storm activity (Lydolph 1977).

Methods

Water chemistry

Sampling was designed to cover a wide regional area with strong gradients in modern precipitation/evaporation values, lake salinity, and brine type (Table 1-1). Lakes chosen for sampling were also spread between low and high elevation sites and between semi-settled town sites, common grazing regions, and government “Protected Areas” in order to capture a gradient of grazing intensity and nutrient loading.

Pelagic surface water samples were collected from lakes in the Altai and Khangai ranges and the Valley of the Great Lakes in 2004 and 2005. Most lakes had only one sampling site; exceptions were the large lakes Uvs Nuur (2 sites) and Khyargas Nuur (3 sites). For small lakes the sample site was the deepest part of the lake as determined with a hand-held acoustic depth meter; for larger lakes the sample site was well off shore at the deepest point reached, up to a depth of about 30 m. Field variables (temperature, specific conductance, pH, dissolved oxygen) were measured with a Yellow Springs Instruments (YSI) multi-parameter water-quality sonde at a depth of about one meter. Water samples for laboratory analysis were collected by hand at a depth of 30 cm in 500 mL amber high-density polyethylene (HDPE) field bottles rinsed three times with sample water. On shore, relative chlorophyll-a content was measured within two hours with a Turner Designs Aquafluor handheld fluorometer. All in vivo chlorophyll-a concentrations were determined on a relative basis compared to a secondary solid standard (P/N 8000-950) set to 800 RFU (relative fluorescence units). Field samples were split at the end of each day into subsamples for further analyses. Twenty mL of unfiltered water was poured into 60 mL HDPE bottles for total phosphorus (TP) and total nitrogen (TN) analyses. All other subsamples were filtered through 45 mm, 0.45 µm pore size low-extractable membrane filters attached to a 60 mL syringe, rinsed with 30 mL of sample water. Subsamples for anion analysis were put in 15 mL HDPE amber bottles without preservative. Subsamples for cation analysis were put in 15 mL HDPE bottles and preserved with high-purity hydrochloric acid to pH below 2. Subsamples for nitrate and ammonia analyses were placed in 60 mL amber HDPE bottles and preserved with sulfuric acid to a pH below 2. In 2004, dissolved organic carbon (DOC) was measured from the same subsample bottle, with a correction to account for a small addition of DOC leached from the plastic bottle itself (mean correction 0.47 mg L^{-1}, standard error = 0.005 mg L^{-1}, n = 5). In 2005, both DOC and dissolved inorganic carbon (DIC) were measured from filtered sub-samples preserved with mercuric chloride in 20 mL amber glass crimp-top vials.

Total phosphorus, TN, nitrate, and ammonia were determined on a Lachat autoanalyzer. Alkaline persulfate dual digestion of TP and TN subsamples (modified from Ameel et al. 1993) was performed in the 60 mL HDPE field bottle to preclude adsorptive loss of nutrients to the bottle wall. Anions were quantified by ion chromatography (Dionex instrument), and cations, trace metals, and silica were determined by ICP-MS (Elmer/Sciex Elan 5000 and Thermo Elemental VG instruments) with precision of 2% or better (R. Knurr, Dept. of Geology and Geophysics, Univ. of Minnesota, personal communication, 2006). In 2004, DOC was analyzed on a Dohrmann Phoenix 8000 UV-persulfate carbon analyzer. Analysis of dissolved inorganic carbon (DIC) on samples from 2004 failed and DIC was instead inferred by speciation calculations from assumed carbonate alkalinity required to achieve charge balance. In 2005, both DOC and DIC were analyzed on a Shimadzu 5000 carbon analyzer.

Diatoms

Collection sites for surface-sediment diatom samples correspond to water sampling sites in each lake and were selected by using a hand-held acoustic depth meter to locate a deep, relatively flat region of the lake bottom. The uppermost one to two centimeters of sediment was collected at each of 64 sites, representing the diatom assemblage being preserved in the lake under current environmental conditions. Sediment in shallow lakes (< 2 m maximum depth) was collected directly from the surface using a disposable pipette; sediment from deeper water sites was collected using a modified Hongve corer (Wright 1990) and transferred to a collection vial with a disposable pipette. All samples were preserved with a 10% formaldehyde solution to prevent degradation. Additionally, sediment from highly saline lakes and lakes with pH > 7.5 were settled in the collection vial, the lake water removed by pipette and the sample diluted with fresh water to prevent further dissolution of diatoms.

In the laboratory, sediment was first cleaned with 10% hydrochloric acid to dissolve carbonates. Samples were then heated in an 85° C water bath with a 30% hydrogen peroxide solution for at least three hours to oxidize organic matter, then centrifuged and rinsed (Renberg 1990). Cleaned material was settled on a cover slip and allowed to dry overnight in ambient conditions. Cover slips were mounted on glass slides using Naphrax or Zrax mounting media. Slides were counted on an Olympus BX-50 microscope at 1000x magnification under oil immersion. Counting followed the methodology of Ramstack et al. (2003), with 400 valves counted per slide on up to six random transects. Specimens were included in a count when greater than 50% of the valve was present. This methodology provided robust abundance estimates given the diversity of the diatom community and was sufficient to reach greater than 85% sampling efficiency in all samples, with up to 95% sampling efficiency in many lakes (Pappas and Stoermer 1996). Standard taxonomic references (e.g. Patrick and Reimer 1966; Krammer and Lange-Bertalot 1986-1991) as well as regional and species-specific primary literature (e.g. Cumming et al. 1995; Nagumo 2003) were used for species identification. A digital photomicrograph was taken of each taxon with a SPOT Insight QE camera attached to the microscope and maintained in a database to ensure consistency in identification among lakes. All diatom taxa counts were converted to percent relative abundance (relative to total diatom counts) before analysis.

Diatoms were present in 57 of the 64 lakes sampled. Five lakes without diatoms had a specific conductance greater than 170,000 $\mu S\ cm^{-1}$ and were presumably too saline to support or preserve a diatom community. Two other lakes yielded very sandy sediment with no preserved valves and may represent a non-depositional zone in the lake. These seven lakes were not considered in further analyses. Over 300 diatom species were recognized in surface sediment counts of the remaining 57 lakes; however, many of the species occurred infrequently. Diatom species present in at least five lakes at any abundance, at least two lakes at an abundance of at least 1%, or one lake at an abundance of at least 5% were retained for statistical analysis. This selection reduced the data set to 158 species, with at least 86% of the total count in each lake remaining after data reduction.

Numerical analyses

Modern diatom communities from the lakes were compared with 30 physical and chemical variables as well as a descriptive factor for 'lake type' (Appendix 1-1). Five lake types were defined, based on general lake morphometry. This descriptive factor was added due to a lack of complete physical data for the lakes; no bathymetric maps are available for the region, and estimates of depth and area in the field were often limited by the large size of the lakes and the small size of the research vessel. Such a wide variety of lakes was sampled, however, that differences in the extent of littoral zone, the total watershed area, and other physical parameters could have an important influence on diatom distributions and community composition. Lakes were described as small (approximately 400 ha or less) or large (>400 ha) and shallow (approximately 5 m or less maximum depth) or deep (>5 m), with a separate category for terminal basins which had exceptionally large catchments and were significantly larger and deeper than other lakes in the data set.

Environmental data are often non-normally distributed, and four transformations (log, inverse, square root, and inverse square root) were tested for their ability to normalize the measured variables. All data, with the exception of pH and the categorical variable for lake type, were log (or log +1 for data containing zeros) transformed to achieve approximately normal distribution before analysis.

Eleven lakes were missing Secchi depth measurements. The missing values were estimated based on a linear regression with total phosphorus (r^2=0.75) or chlorophyll-a (r^2=0.79). Six lakes did not have measured values for chlorophyll-a; these were replaced based on linear regression with total phosphorus (r^2=0.71). Dissolved organic carbon was not measured in Shuvuu Lake and the value was estimated from an average of the three lakes which occur nearest to Shuvuu in a Principal Components Analysis.

Multivariate ordinations were used to explore relationships among lakes and species assemblages. Detrended Correspondence Analysis (DCA) was used to evaluate patterns of diatom community variation among the lakes. Relationships among lakes were explored using Principal Components Analysis (PCA) and between diatoms and environmental data using Canonical Correspondence Analysis (CCA). Outliers in these ordinations were removed from the calibration data set.

Partial constrained correspondence analysis (pCCA) was performed individually on all 30 physical and chemical variables, including all water chemistry data as well as site latitude, longitude, elevation, and lake type, to identify those which were significantly ($p \leq 0.005$) related to diatom community composition. Manual forward and backward selection among individually significant variables and variable groups was conducted using analysis of variance (ANOVA) with 200 unrestricted Monte Carlo permutations.

To assess whether two key variables of interest (SC and TP) each explained a unique and significant fraction of the variance in the diatom species assemblages, a pCCA was run for each variable individually and with other significant variables as conditional co-variables. This allowed for the separation of the unique explanatory power of each variable of interest. All ordination analyses were run in R software with rare species downweighted before analysis using default functions in the vegan package of R (R Development Core Team 2006).

Environmental variables with significant independent explanatory power and important meaning for future paleolimnological work were used to develop transfer functions. These models were developed and the predictive ability assessed using a weighted-averaging approach with bootstrap error estimation in C2 software (version 1.4; Juggins 2003). The strength of each model was assessed using the coefficient of determination (r^2) and the root mean square error (RMSE). Because the same data were used to generate and evaluate the model, these assessments were not entirely independent and the validation step of bootstrapping with 1000 cycles was used to generate a bootstrapped coefficient of determination (r^2_{boot}) and a root mean square error of prediction (RMSEP) which more realistically portrayed error estimates (Fritz et al. 1999).

Results

Environmental variables

A PCA of all environmental data for the 57 sites confirmed that there were two strong gradients, one related to salinity variables including sodium (Na) and specific conductance (SC) and a second gradient related to productivity, including total phosphorus (TP) and Secchi depth (Figure 1-2). The initial calibration set based on 57 lakes spanned a salinity gradient from 40 to over 40,000 µS cm^{-1} and included sodium, chloride, sulfate, and bicarbonate-dominated lakes. Total phosphorus values ranged from 0.007 mg L^{-1} to greater than 2 mg L^{-1}. All five lake types included lakes across the gradient of nutrient concentrations and four of the five types included both fresh and saline lakes; all terminal valley lakes were saline evaporative basins (Table 1-2).

Diatom assemblages

Diatom diversity was high and assemblage characteristics varied widely. Small, shallow lakes were typically dominated by benthic taxa such as *Cocconeis* species, *Nitzschia* species, and other attached forms. Deeper basins had more abundant planktonic flora. Large, saline terminal basins in the valley bottom had relatively low diversity and were often dominated (20-60%) by a single taxon including several unknown and apparently endemic species. *Cyclotella* species (*Cyclotella ocellata*, *Cyclotella pseudostelligera*) were most common in deep, freshwater lakes, as were several species of the genus *Staurosirella*. Many species were found in all lake types, or absent only from the terminal valley lakes (Table 1-3). Certain species, however, were restricted to a single lake type or to groups of lake types with similar characteristics (e.g. shallow lakes regardless of size, or large lakes regardless of depth).

Highly saline lakes had abundant *Amphora* floras; *Anomoeoneis sphaerophora* varieties and *Chaetoceros* spores were also common, though typically low in relative abundance. In more dilute waters the community was shifted to high percentages of *Pseudostaurosira elliptica* and *Staurosirella pinnata* as well as a number of *Cyclotella* species found in lower abundance. Highly eutrophic systems were typically characterized by several nitzschioid diatoms (*Nitzschia bacillum*, *Nitzschia constricta*) as well as *Stephanodiscus minutulus* and an unknown

Gomphonema species, which were not found in abundance in the more nutrient-poor systems.

There were clear community responses along a salinity gradient which were independent of the species shifts along a gradient of increasing nutrient load. Taxonomic groups with strong unimodal responses to SC did not necessarily show strong preferences for TP levels, often occurring in both eutrophic and nutrient poor waters. A different set of species displayed a narrow TP tolerance and a wider threshold for salinity (Figure 1-3). These independent community responses demonstrate the importance of both salinity and trophic status to the diversity, distribution, and composition of the flora in regional lakes.

Data screening

None of the 57 lakes were identified with PCA as clear outliers in their water chemistry, though several were at the ends of specific gradients (Figure 1-2). A detrended correspondence analysis (DCA) for the 158 common diatom species identified three outlier sites, Tsavdon Pond 1 (TSVDP1), Devteeriin Pond 1 (DEVPD1), and Khyargus Lake (KHYARG). The first was a clear outlier in its diatom community structure; the flora of the lake was composed primarily of *Luticola mutica*, *Hantzschia amphioxys*, and *Craticula ambigua*, characteristic soil species which were not found in other regional lakes. This shallow, grassy-bottomed pond was likely ephemeral and frequently dry. The Devteeriin Pond diatom flora was dominated by *Nitzschia bergii* and *Amphora* taxa which were present but rare at other sites in the region. Three separate locations were sampled in Khyargus Nuur and all contained high percentages of an unknown and apparently endemic centric diatom; the locality KHYARG was composed entirely of this taxon, which occurred nowhere else in the calibration set. Two other sample localities from the same lake (KHARG2 and KHARG3) yielded more taxonomically diverse samples, which were retained in the calibration set. The three sites (TSVPD1, DEVPD1, KHYARG) were removed from all subsequent analyses, reducing the final calibration set to 54 lakes and 151 diatom species.

Relationships among diatom assemblages and environmental gradients

In order to establish whether differences in diatom assemblages were strongly associated with the main measured environmental gradients, ordinations of species-environment relationships were evaluated. Gradient length values for the first two

DCA axes were 6.7 and 4.6 respectively, indicating a unimodal response can be assumed along the main gradients for many species (ter Braak 1986).

Eleven variables (Fe, H_2CO_3, water temperature, Ca, pH, Al, Mn, dissolved oxygen, NO_3, site latitude, site longitude) were found to have no individually significant relationship to the diatom data and were eliminated from further analyses. The remaining 19 variables which showed a significant relationship with diatom community data still contained highly redundant sets of environmental predictors. A Pearson correlation matrix was constructed for the remaining variables and 'variable groups' established for variables with an r value >0.9. Manual forward and backward selection within these groups identified the significant variables for each group (Table 1-4). These variables, along with the remaining independent variables, were again assessed using manual forward and backward selection until four variables (lake type, SC, HCO_3, TP) with independent and significant explanatory power were identified.

A CCA for the four most significant variables (Figure 1-4) indicated they explained 19.2% of the variance in diatom distribution (43.2% of the variance accounted for by the initial 19 variable model). The maximum variation in the data set was given on axis one, representing 62% of the explained variance, whereas axis two explained 33%. A CCA biplot of the most significant variables indicated a high level of correlation between axis 1 and the variables SC and HCO_3, which are related to total salinity and brine type. Axis two was strongly correlated with TP, which linked it closely with nutrient load and lake productivity. The distinction of groups based on lake type indicated that lake morphometry also had an important influence on diatom community structure. Small, shallow lakes, for example, had a higher proportion of attached forms regardless of salinity or TP values. These findings support the hypothesis that diatom distributions in the Valley of the Great Lakes are strongly related to both salinity and nutrient concentrations, key variables of interest for paleolimnological investigations. The explanatory power of these variables indicated strong potential for developing effective paleolimnological inference models.

Transfer function

Both SC (2.8 %) and TP (2.6 %) explained an independent and significant portion of the total variation in the calibration set (Table 1-5). A weighted-averaging calculation with classical de-shrinking was used to develop a transfer function for each variable. De-shrinking corrects the overestimation of low values and underestimation of high values caused by averaging in both the regression and calibration steps of model development (initial log TP= -0.7139+0.40472*observed log TP; initial log SC= 1.2086+ 0.62294*observed log SC) (Birks 1990).

One outlier (UVSNRS) was identified in an initial salinity model and was removed from the calibration set for SC before the final transfer function was established. The r^2 values for both models were high, error estimations were low (for SC, r^2=0.91 and RMSE=0.15; for TP, r^2=0.75 and RMSE=0.23) and no trend was apparent in the residuals (Figure 1-5), indicating an effective model with little interaction of confounding variables. Bootstrapped results showed the salinity model to be robust, with relatively small discrepancies between the inferred and bootstrapped results (r^2_{boot}=0.81 and RMSEP=0.37). Bootstrapped correlation and error estimation were more strongly affected for the TP model (r^2_{boot}=0.36 and RMSEP=0.40). The twenty most commonly occurring diatom taxa and their associated calculated TP and SC optima values are given in Table 1-6; all 151 species with optima and tolerances are given in Appendix 1-2.

Discussion

The development of these models was hindered in some ways by the lack of complete data, particularly lake morphometry. The wide variety of lakes in the region resulted in diatom communities partially controlled by factors such as littoral zone extent and maximum water depth, which had no quantitative measure in the calibration set data. However, by using categorical lake-type groupings in the same way used for true categorical variables such as landscape position (Quinlan et al. 2003), the missing data could be satisfactorily accounted for and through variance partitioning was shown to be largely independent of other variables of interest.

Though the sampled ranges of salinity and nutrient concentrations in the 64-lake training set were truncated somewhat by lack of diatom preservation and the removal of outliers, the remaining gradients were long enough to capture the complete tolerance range for many taxa. Some research has criticized the practice of using one data set to create multiple inference models (Anderson 2000); however, the near orthogonal relationship of TP and SC along the first two axes of the CCA (Figure 1-4) demonstrated the independent relationship each variable had with species distribution. Variance partitioning further confirmed the statistical independence of the two gradients.

By carefully examining the diatom community response to each variable, these independent responses to SC and TP can be understood ecologically as well as statistically. The development of a transfer function based on a weighted averaging model depends on the unimodal responses of a group of diatom species along a gradient of interest. In developing two transfer functions from the same data set, ideally a species with a narrow tolerance for one variable of interest has a wide tolerance for the other, leading to transfer functions based on the unimodal responses of unique groups of diatoms to each variable. Species diversity was high across the sampled range of SC and many species had well-defined SC optima but were found across a wide range of TP (Figure 1-3).

Species response to total phosphorus was more varied and often optima were defined by one or two lakes. The definition of TP optima is often problematic compared to other limnologic variables, particularly in shallow lakes where interaction with habitat availability and phosphorus cycling in the sediments is known to affect the benthic community structure (Sayer 2001). Though the species responses along the phosphorus gradient were not as well defined as those for SC, and the bootstrapped error estimates indicated a less robust predictive ability for TP than SC, a relationship between nutrient load and diatom communities is apparent and inferences for TP are still possible (Cumming et al. 1995). The lower predictive ability for the phosphorus model may be related to the stronger response of the diatom community to salinity, to the relatively few samples at the ends of the TP gradient, or to the interactive effects of other variables such as lake type in controlling the diatom community.

Lake type had a potentially confounding role, as some species were found predominantly in shallow lakes, for example, and were rare or absent in deeper lakes. Variance partitioning demonstrated the relationship between community structure and lake type was largely independent of other significant variables. This independence can be understood by examining gradients within each lake type; mean values and ranges for both SC and TP in each lake group subset were similar to those for the entire calibration set (Table 1-2). Additionally, many species were found in all types of lakes. While lake type may have had an effect on the species distribution in the calibration set, it is a relatively stable variable in the lake and is less likely to confound a reconstruction than interactions between fluctuating nutrient load and salinity over short time periods.

In Mongolia, researchers have been recording and studying the diatom flora for over 100 years. The first published investigation of diatom distribution was a report on species found in Lake Hovsgol by Dorogostaïsky in 1904 (Edlund et al. 2001). Diatom distribution studies by Mongolian and international scientists have proceeded through the last century; however, work has been largely focused on reports of occurrences and distribution with little ecological focus.

In recent decades, interest has been building in Mongolia and surrounding regions to use diatoms in paleoclimatological and paleoecological research (e.g. Dorofeyuk and Tarasov 1998; Soninkhishig et al. 2001; Peck et al. 2002; Westover et al. 2006). However, without a quantitative reconstruction tool based on detailed knowledge of the modern relationship between the biology and chemistry, interpretations are speculative. Lacking a quantitative regional calibration set, these and other studies have used assumptions about the distribution of diatoms based on their ecological preferences in North America or based on correlation with other lake core proxies.

The importance of understanding long term drought patterns and frequency in the region has been identified by workers in the past (Dorofeyuk and Tarasov 1998; Soninkhishig et al. 2001; Fowell et al. 2003). This understanding is hampered in all parts of the world by lack of long-term, reliable monitoring data, and the situation is no different in Mongolia where most instrumental records are less than 60 years old and very few have continuous data. Though water-quality assessment in Mongolia is limited, some early efforts at characterizing nutrient impacts, especially to rivers, have heightened awareness of potential problems (Soninkhishig 1998, Stubblefield et al. 2005; Kelderman and Batima 2006). By establishing a quantitative calibration for the ecological preferences of diatoms in Mongolia, future research in these areas will benefit from known relationships between diatom community structure and key environmental variables.

Conclusions

Through coupled sampling of diatoms and modern water chemistry, a relationship has been established between diatom assemblages and two important limnologic variables: specific conductance and total phosphorus. This relationship has been used to develop quantitative inference models which can be used for paleo-limnologic reconstructions to infer past salinity and water quality. Such reconstructions are important to the understanding of recent and long-term changes in water quality and availability.

Western Mongolia is an isolated and poorly understood ecosystem with important links to global biodiversity. Investigating the distribution and diversity of diatoms is a first step toward cataloguing and conserving aquatic resources. In Mongolia, and throughout the developing nations of Central Asia, the availability of freshwater resources is critical to wildlife and human populations as well as to the viability of pastoral subsistence and cash economies. When applied to lake sediment cores, these inference models will provide an important tool to understand the past status and future risk of fresh and saline water bodies in Mongolia. In light of recent warming and resultant reductions in available climatic moisture along with recent increases in grazing pressure, understanding the timing and nature of changes in water quality will be of utmost importance for the continued provision of safe water for herders and quality habitat for wildlife.

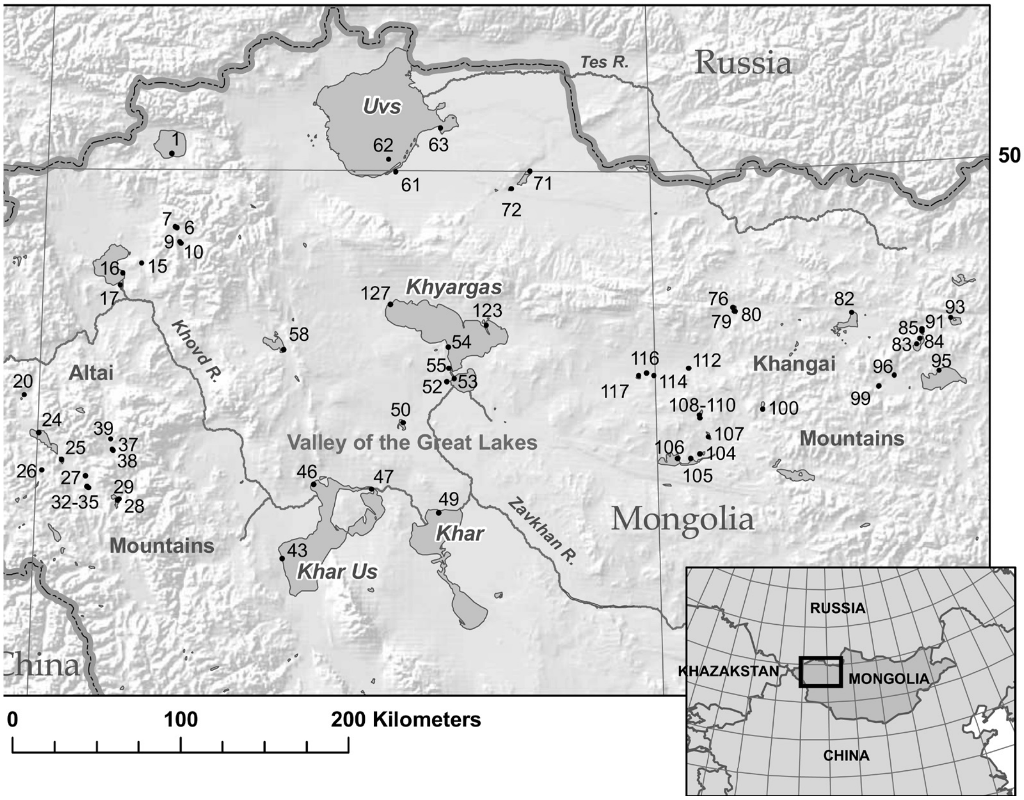


Figure 1-1: Map of Western Mongolia. Sampling locations are labeled by site number (see Table 1-1).

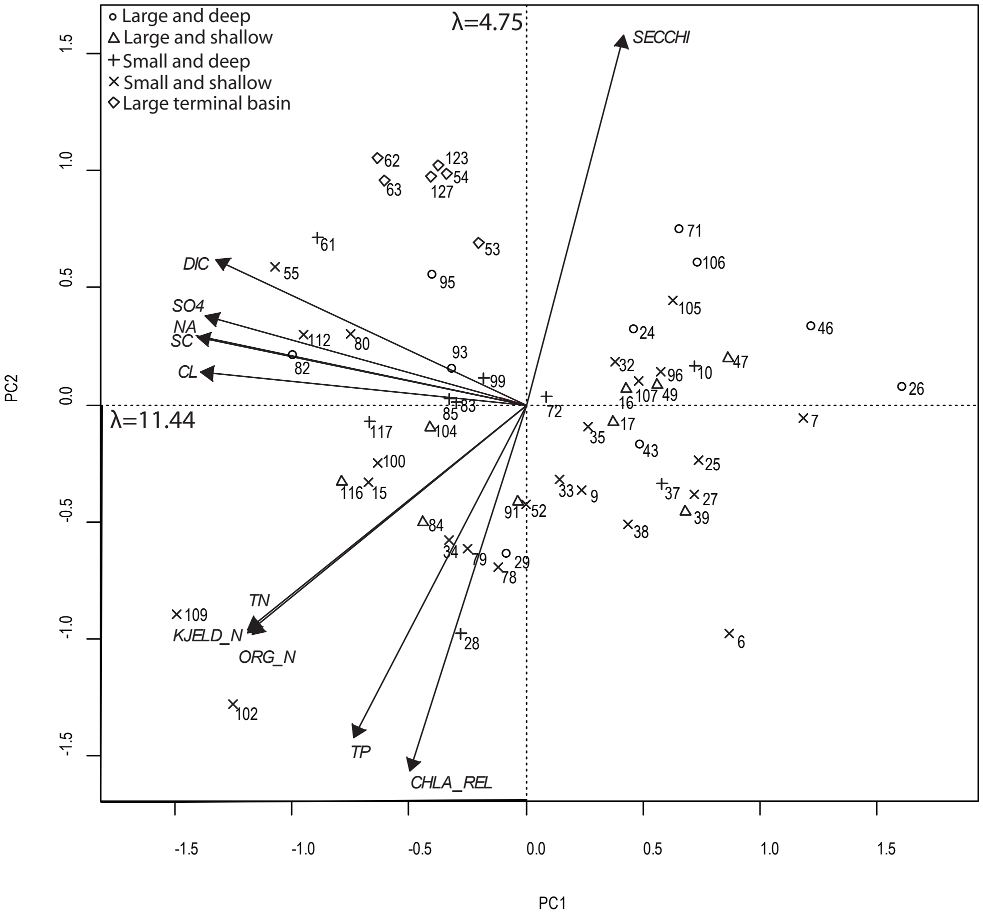


Figure 1-2: A Principal Components Analysis for 57 lakes and associated environmental variables. Site numbers are as in Table 1-1; sites are denoted by symbol for lake type. All physical and chemical variables were used to generate the ordination, but vectors for variables with little explanatory power have been deleted for clarity. CHLA_REL: concentration of chlorophyll a relative to a standard; ORG_N: organic nitrogen; KJELD_N: Kjeldahl nitrogen; TN: total nitrogen; CL: chloride; NA: sodium; SO4: sulfate; DIC: dissolved inorganic carbon; SECCHI: Secchi depth.

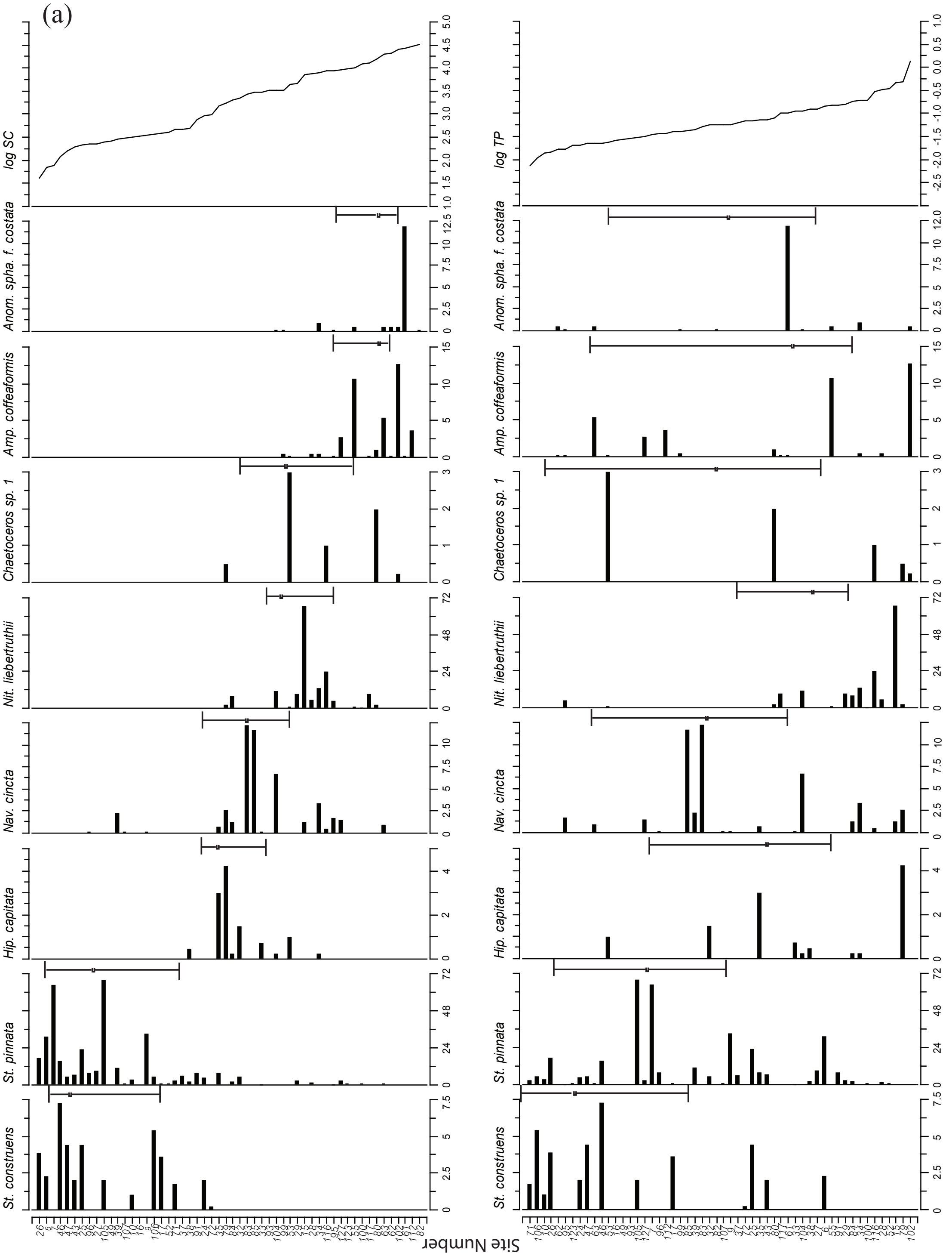
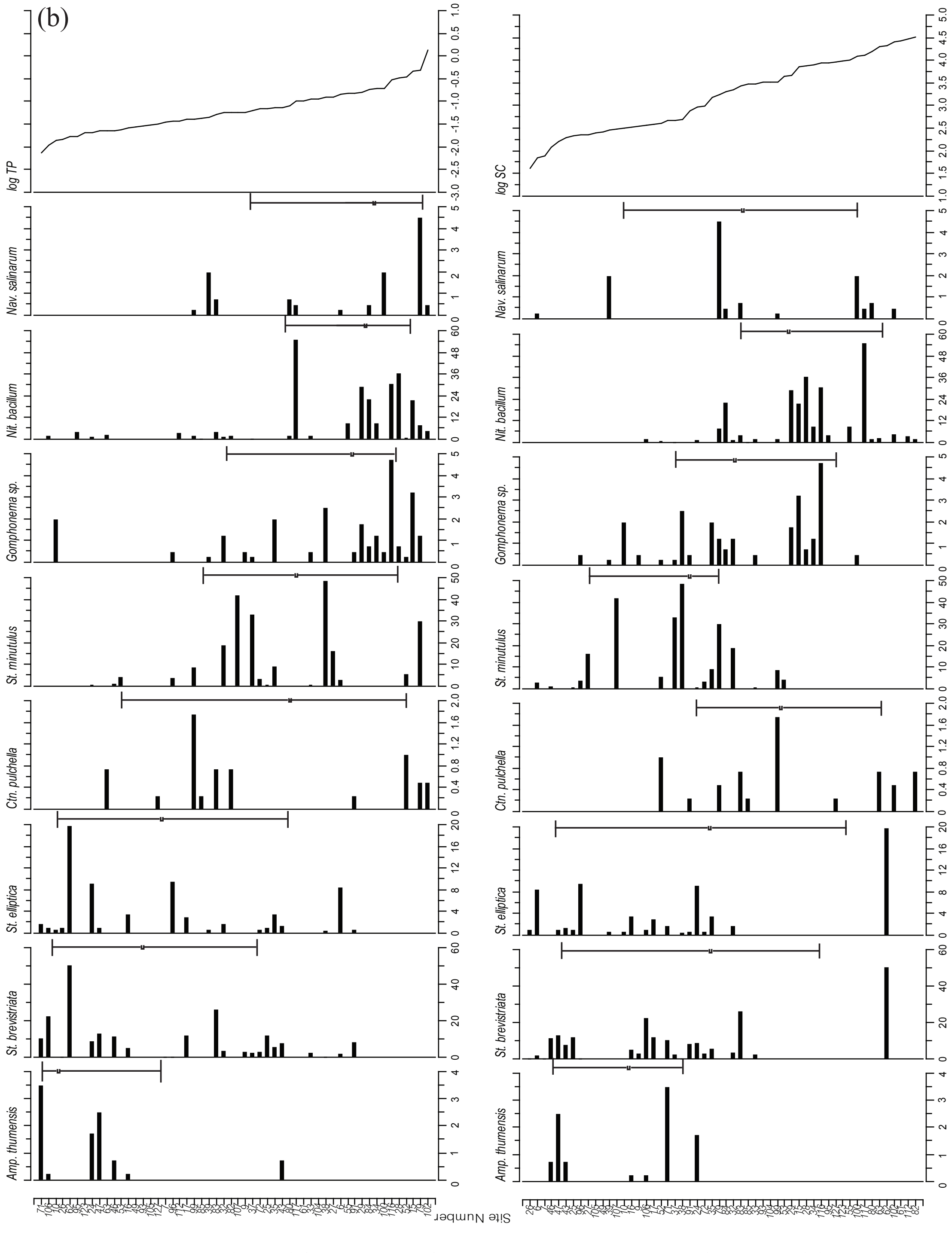


Figure 1-3: Select species responses to specific conductance (SC) and total phosphorus (TP). The same species can have a narrow tolerance for one parameter but a wide tolerance for the other; (a) examples of species with strong salinity preferences (top row) occur in a wide range of nutrient concentrations (bottom row)



(b) examples of species with narrow tolerance for TP (top row) have a wider tolerance for SC (bottom row). The y-axis gives site numbers as in Table 1-1, the x-axes are relative abundance; optima and tolerance on a log scale are given along the right of each bar graph.

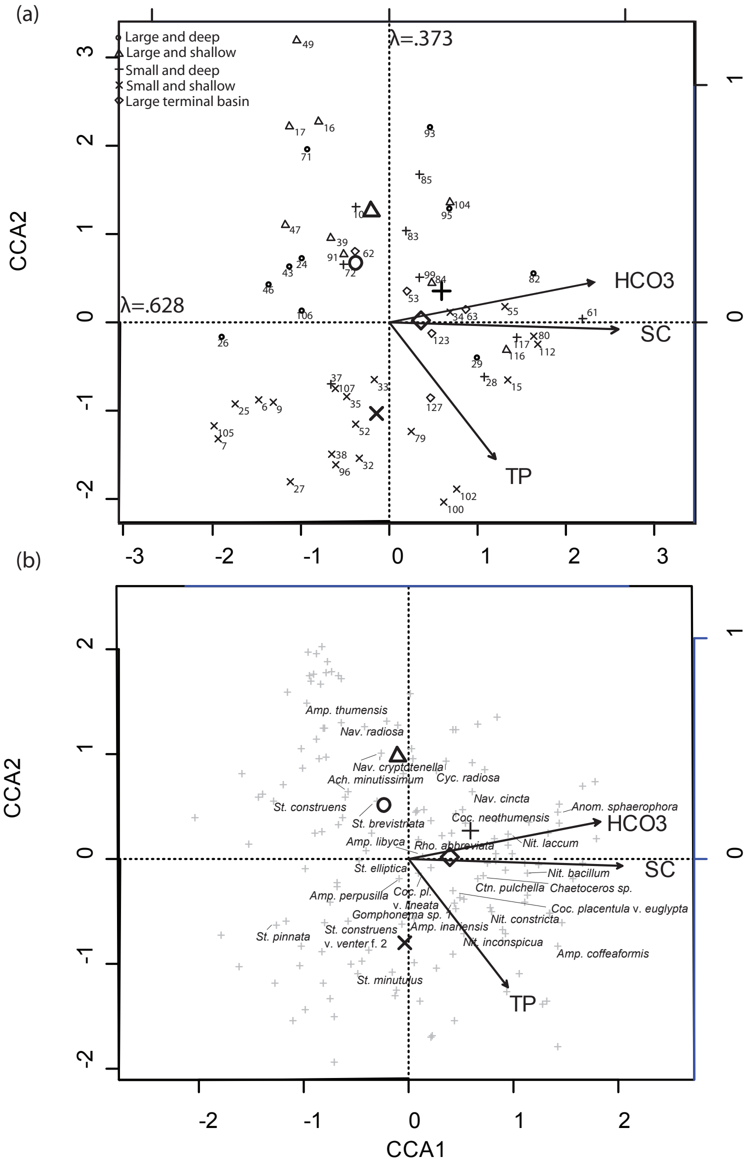


Figure 1-4: A CCA for the 54 calibration set lakes and significant environmental variables. In panel (a) lakes are denoted as lake type symbols and labeled with site number as in Table 1-1, in panel (b) species are shown as crosses and select species are labeled. Species labels refer to the symbol above the first letter unless otherwise indicated. The large, bold symbol in both panels is the centroid for each lake type group. Salinity and brine type are strongly correlated with axis 1; lake productivity variables are strongly correlated with axis 2.

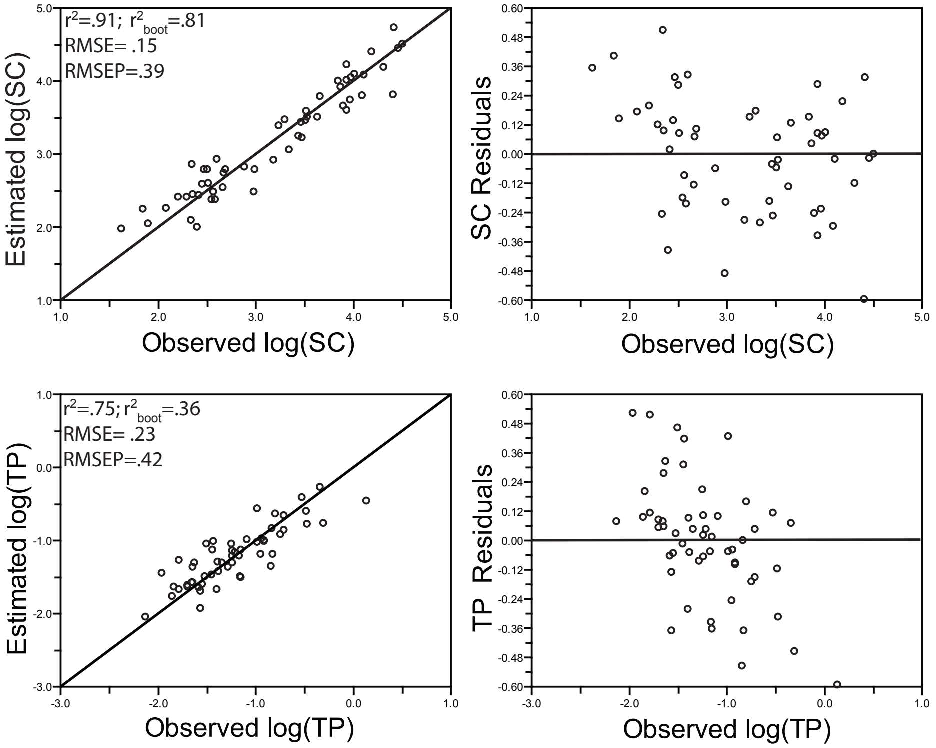


Figure 1-5: Inference models for (a) total phosphorus and (b) specific conductance. One outlier lake (UVSNRS) has been removed from (b) based on visual inspection; the removal raises the r^2 from 0.88 to 0.91 and decreases the RMSEP by 0.04. UVSNRS is dominated (>50%) by *P. brevistriata* and reconstructs poorly within the model.

Site code	Site #	Lat./Long. (decimal degree)	Elevation (m)	Lake type	SC (µS cm^{-1})	TP (mg L^{-1})	HCO_3 (mg L^{-1})
KHOLBO	6	49.7/91.2	2570	SS	69	0.145	41
OLONN2	7	49.7/91.1	2568	SS	78	0.035	45
BARSAL	9	49.6/91.1	2530	SS	357	0.058	145
BUYANT	10	49.6/91.1	2553	SD	319	0.014	174
BAGANR	15	49.5/90.8	1547	SS	7050	0.461	933
ACHITN	16	49.4/90.7	1438	LS	328	0.026	152
ZUUNKH	17	49.4/90.6	1437	LS	383	0.04	185
TOLBON	24	48.6/90.0	2079	LD	951	0.02	509
JJTOLB	25	48.2/90.2	2089	SS	216	0.069	78
ALKHAR	26	48.4/90.6	2510	LD	41	0.015	23
ALALTN	27	48.4/90.4	2211	SS	225	0.123	116
JJDORO	28	48.2/90.7	2394	SD	7500	0.328	264
DOROON	29	48.2/90.6	2394	LD	4543	0.159	314
XOXNR1	32	48.3/90.4	2232	SS	2200	0.056	222
XOXNR2	33	48.3/90.4	2228	SS	3000	0.113	449
XOXNR3	34	48.3/90.4	2225	SS	7900	0.194	751
XOXNR4	35	48.3/90.4	2223	SS	1530	0.071	271
ZAGASN	37	48.5/90.6	2376	SD	473	0.062	184
ARALNR	38	48.5/90.6	2375	SS	489	0.122	174
KHAGNR	39	48.6/90.6	2426	LS	282	0.045	149
KHRUSS	43	47.9/92.0	1157	LD	197	0.071	85
KHRUSN	46	48.3/92.2	1157	LD	120	0.023	72
DALAIN	47	48.3/92.7	1156	LS	161	0.022	86
KHARNR	49	48.2/93.2	1132	LS	262	0.027	138
ZOSTNR	52	48.9/93.3	1032	SS	404	0.34	132
AIRAGN	53	48.9/93.4	1030	TVL	4350	0.024	1315
KHYARG*	54	49.1/93.3	1028	TVL	8610	0.027	2112
SHUVUU	55	49.0/93.3	1019	SS	10300	0.148	5939
UVBAGA	61	50.0/92.9	759	SD	26391	0.105	883
UVSNRS	62	50.1/93.3	759	TVL	20682	0.016	777
UVSNRE	63	50.3/93.3	759	TVL	20363	0.023	1474
BAYANR	71	50.0/94.0	981	LD	465	0.007	224
DNBAGA	72	49.9/93.8	981	SD	977	0.068	295
TSVPD1*	78	49.3/95.6	1635	SS	1040	0.763	239
TSVPD2	79	49.2/95.7	1622	SS	1740	0.492	175
TSVPD3	80	49.2/95.7	1650	SS	15325	0.082	1243
OIGONR	82	49.2/96.6	1680	LD	32276	0.058	1055
KHOLB2	83	49.0/97.1	1940	SD	2772	0.052	654
ULAANR	84	49.1/97.2	1935	LS	1990	0.18	431
KHUNTN	85	49.0/97.2	1939	SD	2958	0.042	667
TSETNR	91	49.1/97.2	1933	LS	771	0.151	272
BELTLK	93	49.2/97.4	2040	LD	3252	0.028	828
TELMEN	95	48.9/97.3	1789	LD	8630	0.017	1096
YALAAT	96	48.9/96.9	1824	SS	220	0.036	108
TAKILT	99	48.8/96.8	1841	SD	3370	0.041	473
TSEGEN	100	48.7/95.9	1882	SS	12430	0.196	667
TSGNPL	102	48.7/95.9	1882	SS	25500	1.363	835
GASHUN	104	48.4/95.3	1520	LS	3300	0.115	748
KHUNT2	105	48.5/95.3	1505	SS	250	0.03	117
DBAYAN	106	48.5/95.1	1481	LD	370	0.011	216
KHOLB3	107	48.6/95.4	1560	SS	296	0.058	96
DEVPD1*	109	48.7/95.3	1540	SS	42900	2.635	2560
TSAGN1	112	48.9/95.3	1458	SS	29083	0.037	523
OLGOIN	116	48.9/94.9	1382	LS	8550	0.296	875
TSAGN2	117	48.9/94.9	1370	SD	12830	0.104	518
KHYAR2	123	49.2/93.6	1028	TVL	9450	0.02	1476
KHYAR3	127	49.3/92.8	1028	TVL	9400	0.031	1470

* These lakes were removed from the final calibration set and were not used in the calculation of averages, standard deviation, or ranges given in Table 2.

Table 1-1: Locations and select environmental data for all calibration set lakes. Site numbers are as in Figure 1-1. Lake types are abbreviated large and deep (LD), large and shallow (LS), small and deep (SD), small and shallow (SS) and terminal valley lakes (TVL); additional variables include specific conductance (SC) and total phosphorus (TP). All environmental data is given in Appendix 1-1.

	Elevation (m)	SC (μScm^{-1})	TP (mgL-1)	HCO_3 (mgL^{-1})
Large and Deep (n=10)				
mean	1727	5085	0.041	442
median	1735	708	0.022	269
st. deviation	533	9946	0.046	410
minimum	981	41	0.007	23
maximum	2510	32276	0.159	1096
Large and Shallow (n=9)				
mean	1595	1781	0.100	337
median	1438	383	0.045	185
st. deviation	423	2749	0.094	289
minimum	1132	161	0.022	86
maximum	2426	8550	0.296	875
Small and Deep (n=9)				
mean	1795	6399	0.091	457
median	1939	2958	0.062	473
st. deviation	636	8499	0.094	247
minimum	759	319	0.014	174
maximum	2553	26391	0.328	883
Small and Shallow (n=21)				
mean	1916	5651	0.201	622
median	1882	1530	0.113	175
st. deviation	466	8524	0.297	1265
minimum	1019	69	0.030	41
maximum	2570	29083	1.363	5939
Terminal Valley Lakes (n=5)				
mean	921	12849	0.023	1302
median	1028	9450	0.023	1470
st. deviation	148	7306	0.006	302
minimum	759	4350	0.016	777
maximum	1030	20682	0.031	1476
All Lakes (n=54)				
mean	1715	5692	0.120	577
median	1735	1865	0.058	284
st. deviation	546	8238	0.203	853
minimum	759	41	0.007	23
maximum	2570	32276	1.363	5939

Table 1-2: Summary statistics for all lakes divided by lakes types. SC=specific conductance; TP=total phosphorus.

LAKETYPE	LD	LS	SD	SS	TVL
Anom. sphaerophora vars.	x	x	x	x	x
Coc. placentula v. euglypta	x	x	x	x	x
Coc. placentula v. lineata	x	x	x	x	x
Cyc. radiosa	x	x	x	x	x
St. pinnata	x	x	x	x	x
Nav. cryptotenella	x	x	x	x	x
Nit. lacuum	x	x	x	x	x
Rho. abbreviata	x	x	x	x	x
Amp. perpusilla	x	x	x	x	x
Amp. libyca	x	x	x	x	x
Nit. constricta	x	x	x	x	x
Gomphonema sp.	x	x	x	x	
St. elliptica	x	x	x	x	
Nit. bacillum	x	x	x	x	
St. construens	x	x	x	x	
Fra. tenera	x	x	x	x	
Gyro. spencerii					x
Cyclotella sp. KYW					x
Ach. saccula	x	x			
Amp. thumensis	x	x			
Cyc. ocellata	x	x			
Den. kuetzingii	x	x			
Ach. exigua	x				
St. construens f. 1	x				
St. lapponica	x				
Geis. schoenfeldtii	x				
Cym. neoleptoceros		x			
Cym. cesatii		x			
Nit. sublinearis		x			
Nit. palea		x			
Cal. bacillum			x	x	
Nav. menisculus v. upsaliensis			x	x	
Nav. veneta			x	x	
Nit. frustulum			x	x	
Coc. placetula v. baikalensis				x	
Fra. subsalina				x	
Mar. martii				x	
Nav. cryptocephela				x	
Fra. capucina			x		
Ach. lanceolata v. dubia			x		
Hip. hungarica			x		
Nav. eidrigiana			x		
Cym. minuta		x		x	
Hip. capitata		x		x	
Sur. peisonis		x		x	
Nav. crucicula		x		x	

Table 1-3: Select species occurrences by lake type. An ‘x’ indicates the species was present in more than one lake in a given category. Many species are found in all or most lake types but some have clear preferences.

Group	Within group r^2	significant variables retained for further testing
Salinity variables: specific conductance (SC), Na, SO_4, Cl, K, Mg	0.97	SC, Na, SO_4, Cl, K
Nitrogen variables: total N, organic N, Kjeldahl N	0.97	Kjeldahl N
Inorganic carbon variables: CO_3, HCO_3, DIC	0.99	HCO_3
Remaining independent variables: Si, Elevation, TP, dissolved organic carbon (DOC), lake type, NH_4, Secchi		All

Table 1-4: 'Variable groups' used for initial significance testing and selection; variables with r^2>0.90 were grouped together.

variable	*total variance explained (significance)*	*unique variance explained (significance)*
TP	3.3% ($p \leq 0.005$)	2.6% ($p \leq 0.005$)
SC	5.4% ($p \leq 0.005$)	2.8% ($p \leq 0.005$)
HCO_3	4.8% ($p \leq 0.005$)	2.4% ($p \leq 0.05$)
5 lake type classes	9.2% ($p \leq 0.005$)	8.5% ($p \leq 0.005$)

Table 1-5: Variance partitioning for select variables. Total variance includes interaction between variables; unique variance is attributable to the variable of interest in the absence of all other variables. Lake type represents the combined explanatory power of all five lake type variables.

Taxa	*# occurrences*	*max. %*	*TP optima ($mg L^{-1}$)*	*SC optima ($\mu S cm^{-1}$)*
Achnanthidium minutissimum	26	17	0.045	295
Amphora inariensis	20	42	0.077	1950
Amphora libyca	32	15	0.114	1738
Amphora perpusilla	31	26	0.047	1622
Cocconeis neothumensis	17	19	0.023	6918
Cocconeis placentula v. *euglypta*	20	8.5	0.089	4266
Cocconeis placentula v. *lineata*	20	14.25	0.067	1995
Cyclotella radiosa	27	53	0.030	2630
Navicula cincta	17	11.75	0.077	3890
Navicula cryptotenella	20	20.5	0.051	708
Nitzschia bacillum	26	55	0.416	12022
Nitzschia constricta	18	9.25	0.123	11481
Nitzschia inconspicua	17	5.5	0.141	6457
Nitzschia laccum	27	69.25	0.117	10715
Pseudostaurosira brevistriata	27	50.75	0.015	1096
Pseudostaurosira elliptica	20	32.75	0.018	912
Rhoicosphenia abbreviata	18	13.5	0.134	1413
Staurosirella pinnata	34	68	0.033	96
Staurosira construens v. *venter* f. *2*	21	32.75	0.087	229
Stephanodiscus minutulus	18	48.75	0.138	437

Table 1-6: The 20 most common diatom species with occurrence data and calculated optima for total phosphorus (TP) and specific conductance (SC). Optima and tolerances for all calibration set species are given in Appendix 1-2.

Chapter 2

Diatom biodiversity in Mongolia: New and poorly known cyclotelloid diatoms from western Mongolia

Abstract

In 2004 and 2005 a hydro-biological survey explored the little-known aquatic systems of the Valley of the Great Lakes, a closed basin region in western Mongolia with a wide variety of fresh and saline lakes. Sixty-four lakes were sampled in order to document the diversity of diatom species and the controls on their distribution in the region. Over 300 species were identified, including new distributional reports for nearly 100 taxa and the identification of several new species. However, despite previous reports of at least16 different species of cyclotelloid diatoms in Mongolia, only six known species from three cyclotelloid genera were found. In addition, three new species, each with limited distribution, were identified. The distribution, taxonomy, and morphology of poorly known species are discussed and three new species, *Puncticulata khyargusiana*, *Cyclotella uuregensis*, and *Cyclotella buyantsogii* are provisionally described.

Introduction

In 2004 and 2005 a hydro-biological survey was conducted to characterize the diversity and distribution of diatoms in the aquatic systems of the internally drained Valley of the Great Lakes (VOGL) in western Mongolia. The VOGL has at least three major terminal basins in the central valley and many more isolated basins in the Altai and Khangai Mountains as well as numerous flow-through systems throughout the region. Over 300 diatom species were identified in regional lakes including at least 150 species that had not been previously reported in Mongolia (Edlund et al. 2001; Appendix 2-1).

The genus *Cyclotella* (Kütz.) Breb. is a diverse group of marine and freshwater species typically characterized by a flat to tangentially or concentrically undulate valve face with a distinct marginal area composed of areolae grouped into fascicles (Round et al. 1990). Recognition of significant variability in other features of the genus, such as the number, placement, and morphology of the rimoportulae and fultoportulae has led to the recent separation of several genera from the group (e.g. *Cyclostephanos*, *Discostella, Puncticulata, Brevisira*; Theriot et al. 1987; Houk and Klee 2004; Håkansson 2002; Krammer 2001) and broad agreement that "*Cyclotella*" is an unnatural group (Julius 2000). Often an important group of indicator species in environmental monitoring and paleo-limnology, the need to clearly delineate cyclotelloid species and properly characterize their environmental tolerances are important to many applications (Wunsam et al. 1995). Continued study of the genus with light and scanning electron microscopy also supplements molecular datasets with morphological data and refines our understanding of the biogeography and phylogenetic relationships within this group.

The relationship between diatom communities and water chemistry in western Mongolia has been used to develop a calibration set for paleoecological reconstructions in the region (Shinneman et al. in press). Because cyclotelloid species are often difficult to properly identify (Håkansson 1993; Cremer et al. 2001), are important indicators in many environments (Wunsam et al. 1995; Cremer et al. 2001; Smol et al. 2005), and have been used to compare calibration sets across arid and semi-arid regions (Carvalho et al. 1995), special focus was given to the identification of this group in Mongolia during development of the calibration set. Here we describe the ecology and distribution of cyclotelloid diatoms in western Mongolia including a new distributional report for one species, *Cyclotella choctawhatcheena* Prasad, and the description of three new species, *Puncticulata khyargusiana* prov. nom., *Cyclotella buyantsogii* prov. nom. and *Cyclotella uuregensis* prov. nom.

Study Area

The Valley of the Great Lakes lies in the far west of Mongolia, bounded by the Altai Mountains to the west, the Khangai Mountains to the east, and the Gobi Desert to the south (Fig. 2-1). The Great Lakes region is part of the endorheic Central Asian Basin and includes several smaller closed drainage basins with lakes ranging from fresh to hypersaline (Dulmaa 1979; Shinneman et al. in press). Many of the large terminal basins in the valley are believed to be remnants of large Tertiary or Quaternary paleo-lakes (Grunert, et al. 2000). Sample sites included three large terminal basins in the area, Khyargus, Uvs, and Uureg. There are additionally numerous large and small ephemeral ponds, playa lakes, floodplain lakes, and dune-blocked lakes.

Lakes sampled for development of the calibration set ranged from dilute to hyper-saline (40-200,000 μS cm^{-1}). Saline lakes (SC>3000 μS cm^{-1}) were common in the region (Table 2-1; Shinneman et al. in press). Large lakes in the central valley are terminal basins for the internally drained Central Asian basin. Many small lakes and pools were also highly saline; most ions were more concentrated in lakes and pools as compared to spring and groundwater sites indicating a strong evaporative signal for standing waters. At the highest concentrations ionic composition was dominated by sodium chloride, whereas dilute lakes were more commonly composed of sulfate and carbonate salts. Trophic status index (TSI) calculations (Carlson 1977) made using TP and Secchi depth measurements indicated that most lakes, fresh and saline, were eutrophic to hyper-eutrophic at the time of sampling in late summer. Nitrogen to phosphorus ratios showed that most lakes were strongly P-limited (Table 2-1).

Materials and Methods

Lakes over 0.5 meters in depth were sampled by inflatable canoe at the deepest part of the lake as measured with a hand-held acoustic depth meter. Shallow lakes and pools were sampled by wading to the deepest point. Most lakes had only one pelagic sampling site; exceptions were the large lakes Uvs Nuur with two sites and Khyargas Nuur with three sites (Figure 2-1). Water samples, plankton tows, and sediment samples were collected at the same time and in the same location. Collection procedures and analytical methods for water chemistry are described in Shinneman et al. (in press).

For diatoms, the top one to two centimeters of sediment were collected at the deepest sounding in each of 64 lake sites, representing the diatom assemblage being preserved in the lake under current environmental conditions. These assemblages represent a spatially and temporally integrated sample from the both the littoral zone and water column that have been deposited in the deep basin through sediment focusing. Sediment in shallow lakes (< 1 m maximum depth) was collected directly from the surface using a disposable pipette; sediment from deeper water sites was collected using a modified Hongve corer (Wright 1990) and transferred to a collection vial with a disposable pipette. Diatoms were also collected from the water column with a 6 m vertical tow using a 10 µm-mesh plankton net. All samples were preserved with a 10% formaldehyde solution to prevent degradation. Additionally, sediment samples from highly saline lakes and lakes with pH greater than 7.5 were settled in the collection vial, the lake water removed by pipette and the sample diluted with bottled water to prevent further dissolution of diatoms. Plankton tows from a previous field season in 2000 were also used for comparison in Khyargus and Uureg lakes.

In the laboratory, sediment was first cleaned using 10% hydrochloric acid to dissolve carbonates. Samples were then heated in an 85° C water bath with a 30% hydrogen peroxide solution for at least three hours to oxidize organic matter, then centrifuged and rinsed (Renberg 1990). Cleaned material was settled on a cover slip and allowed to dry overnight in ambient conditions. Cover slips were mounted on glass slides using Naphrax or Zrax mounting media. Slides were counted on an Olympus BX-50 microscope at 1000x magnification under oil immersion following Shinneman et al. (in press). Standard taxonomic references (e.g. Patrick and Reimer 1966; Krammer and Lange-Bertalot 1997) as well as regional and species-specific primary literature were used for species identification. Each taxon was imaged with a SPOT Insight QE digital camera attached to the microscope and images maintained in a database to ensure consistency in identification among lakes. Cleaned material was prepared for scanning electron microscope (SEM) study by settling cleaned material on a coverslip under ambient conditions. Coverslips were affixed to a carbon coated stub then coated in 20 nm of gold. Material was examined under 15-20 kV accelerating voltage in a JEOL-JSM-6060LV SEM.

Environmental optima and tolerances with bootstrap error estimation were calculated for all species (Shinneman et al. in press) using a weighted-averaging approach and C^2 software (version 1.4; Juggins 2003).

Results

Overall diatom distribution and ecology

Five lakes were sampled and found to have no diatoms present; these had a specific conductance greater than 170,000 µS cm^{-1} and were presumably too saline to support or preserve a diatom community. In the remaining lakes, over 300 taxa were identified, including over 100 taxa that had not been previously reported from Mongolia (Appendix 2-1). Although 16 cyclotelloid species have been previously reported in Mongolia (Edlund et al. 2001), and approximately 100 species are currently recognized worldwide (Round et al. 1990), the Valley of the Great Lakes survey revealed only six known cyclotelloid species (*Puncticulata radiosa* (Lemmermann) Håkansson, *Cyclotella meneghiniana* Kütz*, C. ocellata* Pant., *C. choctawhatcheeana* Prasad*, C. siberica* Skabitschevsky, and *Discostella pseudostelligera* (Hust.) Houk & Klee). Four of the six species, *Cyclotella ocellata*, *Discostella pseudostelligera*, *C. meneghiniana*, and *C. siberica,* have been previously reported from Mongolia (Edlund et al. 2001, 2003) and this study adds to their known distribution (Figures 2-2, 2-12). One species, *Puncticulata radiosa*, has likely been previously identified in the region, but reported as C. *bodanica* Eulenstein, *Cyclotella lemanensis* (O.Müll.) Lemmerman, or *C. comta* (Ehrenb.) Kütz.; Edlund et al. 2001). *Cyclotella choctawhatcheeana* is reported here for the first time from Mongolia, although previous reports of *Cyclotella caspia* Grunow from the region (Peck et al. 2002; Edlund et al. 2001) are likely mis-identifications of *C. choctawhatcheeana*. Three additional cyclotelloid taxa were not identifiable and found with limited distributions; their distributions, environmental optima, and provisional descriptions as *Puncticulata khyargusiana, Cyclotella uuregensis* and *Cyclotella buyantsogii*, are provided below.

Puncticulata radiosa was the most widely occurring species, found in 27 lakes that ranged from 0.007 to 0.330 mg L^{-1} total phosphorus and 69 to 8630 µS cm^{-1} specific conductivity (Table 2-2). *Discostella pseudostelligera* was also relatively widespread, found in nine lakes. *Cyclotella ocellata* was found in only five lakes. *Cyclotella choctawhatcheeana* was found in two lakes, notably the more saline lakes, Uvs Nuur and Oigon Nuur. *Cyclotella siberica* and the newly described species *Puncticulata khyargusiana, C. uuregensis*, and *C. buyantsogii* were each found in only one lake. Calculated optima and tolerances for those species included in the calibration set occur across the ranges of TP and SC (Table 2-2; Appendix 1-1)

The undescribed species (*Puncticulata khyargusiana*, *Cyclotella uuregensis*, *C. buyantsogii*), and select taxa which required detailed taxonomic study for identification (e.g., *C. siberica, C. choctawhatcheeana*) are treated in greater detail.

Systematic and ecological treatment of select taxa

Puncticulata khyargusiana **A.L.C. Shinneman, M.B. Edlund, M.L. Julius, N. Soninkhishig,** ***prov. nom.***

Figures 2-3 and 2-4

Holotype: Marked specimen (Fig. 2-3) on slide M1490, deposited at the Academy of Natural Sciences, Philadelphia (ANSP).

Isotypes: Slides and material of collection M1490 deposited in M. B. Edlund personal collection (M1490a; Science Museum of Minnesota), in National University of Mongolia Diatom Herbarium (M1490b), and in the California Academy of Sciences (CAS; M1490c)

Paratypes: Slides and material of collection M786 deposited in in M.B. Edlund personal collection (Science Museum of Minnesota; M786a), in National University of Mongolia Diatom Herbarium (M1490b), and in CAS (M786c). Collection M786 is an epipelic collection from Khyargus Nuur (lake), Uvs aimag, Mongolia, 1028 m elevation, (49.16 N, 92.48 E), coll: M. Edlund 19 July 2000.

Type locality: Khyargus Nuur (lake), Uvs aimag, Mongolia, site 123, surficial sediment, 1028 m elevation, (49.08 N, 93.32 E), coll: M1490 by M. Edlund, A. Shinneman, 20 July 2005.

Description: Cells solitary. Valves round, diameter 9-25 µm. Central area slightly convex or concave, diameter 7-17 µm, and ornamented with poorly organized pattern of areolae and one to several central fultoportulae with three satellite pores. Central area with hyaline margin (0.86-1.8 µm wide) at junction with marginal area. Marginal area with 10-17 striae in ten microns. Every 2-3 costa is thickened and has a marginal fultoportulae with two satellite pores. A single labiate process occurs on the valve face.

Etymology: The specific epithet refers to the only location this taxon can be found and where it is presumed endemic: Khyargus Nuur, Uvs aimag, Mongolia.

Diagnosis: Most features of the *Puncticulata khyargusiana* are similar to the more widespread species *P. radiosa*. Comparisons of *P. khyargusiana* to distributions of *P. radiosa* from two other large and saline lakes, Belt and Telmen, and across all lakes where *P. radiosa* is present showed the same characteristics in number and placement of features such as the central fultoportulae, marginal fultoportulae, and labiate processes. Many characteristics of the valve face, including the valve diameter, central area diameter, and number of marginal straie in ten microns were indistinguishable between the two groups and were not statistically different from one another (Student's t-test $p>0.01$; Figure 2-3; Figure 2-5). The two distinguishing characters for *P. khyargusiana* are the fewer and more poorly organized central area ornamentation and the wider hyaline spacing at the junction of the central and marginal areas (Figures 2-3, 2-4, 2-5). The width of the hyaline ring is significantly wider ($p<0.005$) in *P. khyargusiana*.

Distribution: *Puncticulata khyargusiana* is found only in Khyargus Nuur (Fig. 2-1), a large terminal basin in the center of the Valley of the Great Lakes with an average conductivity of 9153 µS cm^{-1} (range 8610 to 9450 µS cm^{-1}, n=3; Table 2-1) and average total phosphorus of 0.03 mg L^{-1} (range 0.020-0.031 mg L^{-1}, n=3; Table 2-1). Khyargus Nuur is large and at least 30 m deep. *Puncticulata khyargusiana* was the only planktonic diatom present in the lake. In contrast, the more common *P. radiosa* was found across a wider variety of environments in western Mongolia including small lakes only a few meters deep and large lakes with over 20 m maximum depth. *Puncticulata radiosa* was found in lakes with conductivity that ranged from 69 to 8630 µS cm^{-1} and total phosphorus from 0.007 to 0.330 mg L^{-1}. The TP range for *P. khyargusiana* is well within the range for *P. radiosa* in the region; however, the salinity of Khyargus Nuur exceeds the measured range for the more common form.

Cyclotella uuregensis **A.L.C. Shinneman, M.B. Edlund, M.L. Julius, N. Soninkhishig, *prov. nom.*** (Figures 2-6 and 2-7)

Holotype: Marked specimen (Fig. 2-6) on slide M861 deposited at ANSP.

Isotypes: Slides and material of collection M861 deposited in M. B. Edlund personal collection (M861a; Science Museum of Minnesota), in National University of Mongolia Diatom Herbarium (M861b), and in CAS (M861c).

Type locality: Uureg Nuur (lake), Uvs aimag, Mongolia, site 1, surficial sediment, 1425 m elevation, (50.01 N, 91.03 E), coll: M861 by M. Edlund, 1 July 2000.

Description: Valves round and heavily silicified with a radially undulate face with 3-6 (most commonly 5) depressions/elevations in the central area. Valves are 6-16 µm in diameter, with a central area diameter to valve diameter ratio of 0.5-0.6. Marginal striae occur in a density of 15-20 in 10 µm and are evenly spaced but not always of uniform length. A single central fultoportula is visible slightly off-center within a valve-face depression (Figure 2-6). The internal expression of the single central strutted process is a short tube surrounded by three satellite pores. In the SEM marginal striae are composed of two parallel rows of side-by-side round openings. Marginal fultoportulae with two satellite pores occur on a recessed secondary costae approximately every third to fifth costae. The external openings of fultoportuale are unornamented. A single, unstalked rimoportule is located on a recessed costa opposite the central fultoportule. The rimoportule is oriented tangentially on the valve interior and has a simple, unornamented external opening (Figures 2-6 and 2-7).

Etymology: This taxon is named after its type and only known locality, the lake Uureg Nuur in Uvs aimag, Mongolia.

Diagnosis: *Cyclotella uuregensis* has many features in common with other small *Cyclotella* species. Internal features such as the position of the central strutted process and its three satellite pores, and the position and number of marginal strutted processes are similar to *Cyclotella ocellata, C. polymorpha, C. comensis,* and allied species (Håkansson 2002; Edlund et al. 2003). However, the deeply radially undulate surface and distinctive patterning clearly distinguishes *C. uuregensis* it from other *Cyclotella* species. The undulate surface is most similar to *Cyclotella comensis* in the light microscope (Håkansson 2002); however, the undulations of *C. uuregensis* are more numerous and more pronounced. Furthermore, the central area of *C. comensis* is slightly tangentially undulate, a feature not seen in *C. uuregensis*.

Distribution: This diatom has been found only in Uureg Nuur, a closed basin lake at 1425 m elevation in the Altai Mountains, near Mongolia's northwest border with Russia (Fig. 2-1). The lake was saline (6100 µS cm^{-1}) with a pH of 9.08. Uureg Nuur had relatively high nutrient concentrations (0.08-0.1 mg L^{-1} total phosphorus; 0.22-0.24 mg L^{-1} total nitrogen) but a Secchi depth of over 5 m. During surveys in 2000 and 2004 this diatom was the sole member of the planktonic diatom community in this lake.

Cyclotella buyantsogii* A.L.C. Shinneman, M.B. Edlund, M.L. Julius, N. Soninkhishig, *prov. nom.

Figures 2-8 and 2-9

Holotype: Marked specimen (Fig. 2-8) on slide M1129 deposited at ANSP

Isotypes: Slides and material of collection M1129 deposited in M. B. Edlund personal collection (M1129a; Science Museum of Minnesota), in National University of Mongolia Diatom Herbarium (M1129b), and at CAS (M1129c).

Type locality: Buyantsog Nuur (lake), Uvs aimag, Mongolia, site 10, surficial sediment, 2553 m elevation, (49.62 N, 91.12 E), coll: M1129 by M. Edlund, A.L.C. Shinneman, N. Soninkhishig, 04 August 2004.

Description: Valves round, diameter 6-15 µm, 13-18 marginal striae of equal length per 10 µm. In the light microscope valves appear flat with 1-3 central pores typically visible. A faint tri-lobate undulation can be seen in some planes of focus, but is not clearly visible in all specimens (Fig. 2-8). In SEM the valve face has three shallow undulations giving this very faint tri-lobate 'shadow' sometimes visible in the light microscope (Fig. 2-8 and 2-9). The marginal processes are located on every 4-7 costa. The rimoportulae occurs on the valve face, opposite the central strutted process and can be seen in the light microscope in larger specimens. Externally, the striae are composed of two parallel rows of round openings with a larger internal opening through which trans-radial costae are visible. Both the marginal and central fultoportulae have two satellite pores and no ornamentation on the external openings.

Etymology: This taxon is named in honor of Mr. B. Buyantsog from Ulaangom, Mongolia. The lake in which this diatom was found has no formal name and was also unofficially named in his honor. Buyantsog was the local coordinator of two field expeditions in western Mongolia.

Diagnosis: In the light microscope this diatom bears a strong resemblance to *Cyclotella cyclopuntca* Hakansson et Carter; however, the hollows or "pearls" near the valve/ margin junction which characterize *C. cyclopuncta* are absent. The diatom also resembles *Cyclotella atomus* Hustedt, having the same size range and generally similar appearance on the valve face; however, *C. atomus* is distinguished in LM by the dark lines ("Schattenlinien") from marginal fultoportulae that occur on every third to fifth striae; these dark lines are absent in *C. buyantsogii*. The construction of the striae in *C. buyantsogii* as visible in the SEM is also distinctly different from *C. atomus*.

Distribution: Buyantsog Nuur is a small (~10 Ha) and deep (18 m) lake at 2553 m elevation in the Altai Mountains. The origin and age of the lake have not been investigated here nor have they been previously published. Based on the observed depth to area ratio and the surrounding peri-glacial environment, it resembles many kettle lakes in other recently glaciated parts of the world. The lake is dilute (319 µS cm^{-1} specific conductivity) and has moderate nutrient concentrations (0.014 mg L^{-1} TP and 0.87 mg L^{-1} TN) with a Secchi depth of 3.4 m. *Cyclotella buyantsogii* was not found elsewhere in the modern survey decribed here, but has been found down-core in another lake, Bayan Nuur. Bayan was larger in area than Buyantsog but similarly deep (17.9 m maximum measured depth), dilute (370 µS cm^{-1}) and oligo- to meso-trophic (0.011 mg L^{-1} TP).

***Cyclotella choctawhatcheeana* Prasad in Prasad et al.** (Figures 2-10 and 2-11)

Description: Valves round, 6-13 µm in diameter, with a colliculate and strongly tangentially undulate central area occupying approximately 2/3 of the total valve diameter. The raised half of the undulation has 1-9 pores which are the external openings of the central fultoportulae (Figures 2-10 and 2-11). Internally the central area is smooth except for the internal openings of the central fultoportulae, which have three satellite pores. Marginal strutted processes with two satellite pores occur every on every second to third marginal costae (Figure 2-11).

Diagnosis: The diatom bears some resemblance to *Cyclotella caspia*, but *C. caspia* has

a smooth valve face (Håkansson et al. 1993). It also has similarities with *Cyclotella tuberculata*; however, *C. tuberculata* has marginal fultoportula every 3-5 costae in contrast to every 2-3 costae in *C. choctawhatcheeana*. Mongolian populations of this diatom fall within the morphological range given for *C. choctawhatcheeana* by Carvahalo et al. (1995), but it exceeds the size range and the number of central strutted processes given in the original description of *C. choctawhatcheeana* by Prasad et al. (1990).
Distribution: *C. choctawhatcheeana* was identified in two lakes in western Mongolia, Oigon Nuur and Uvs Nuur. Oigon Nuur was a large, isolated saline lake at 1680 m on the flanks of the Khangai Mountains. Conductivity in the lake was 32,276 µS cm^{-1}. The nitrogen to phosphorus ratio in the lake is high; total phosphorus was 0.058 mg L^{-1} while TN was 4.85 mg L^{-1}. This was the only centric diatom found in Oigon lake and it was found in abundance in the samples from the sediment water interface (relative abundance = 15.75%). Uvs Nuur is a large, deep, and saline (over 20,000 µS cm^{-1}) terminal basin with moderate nutrient concentrations (0.02 mg L^{-1} TP). *Cyclotella choctawhatcheeana* was identified in both surface sediment samples taken from different bays in the lake, at 1% and 19.5% relative abundance.

Previous studies of saline lakes in Mongolia have identified *Cyclotella caspia* in subfossil sediment samples from Lake Telmen (Peck et al. 2002) and in recent material from Lake Erkhel (Edlund et al. 2001). Both of these lakes are also relatively large and highly saline (8630 µS cm^{-1} for Telmen and over 20, 000 µS cm^{-1} for Erkhel). These taxa have been mistaken for one another in many other saline regions (Cavahalo et al. 1995). Reanalysis of material from Telmen and Erkhel indicates those populations are also *C. choctawhatcheeana*. *Cyclotella choctawhatcheeana* was originally described from a brackish to marine setting in the U.S. Gulf of Mexico (Prasad et al. 1990) and has since been identified in many inland brackish to saline lakes (Carvalho et al. 1995).

***Cyclotella siberica* Skabitschevsky** (Figures 2-12 and 2-13)
Description: Valves round, 5-7 µm in diameter with a ratio of valve diameter to central area diameter between 1.4 and 1.6 (Figure 2-12). Few features are visible in the light microscope; the valve face appears to be blank, surrounded by equal length striae with a density of 16-19 in 10 µm. In SEM, the diatom has a nonporous flat valve face with small siliceous granules arranged radially on the exterior of the central area (Figure 2-13). Internally, the central area is surrounded by short, wide alveolar openings with trans-radial costae visible in some specimens. Marginal fultoportulae with two satellite pores occur on every sixth to tenth costae. A single unstalked rimoportule is located on a costa, opposite the central strutted process. The internal opening of the central fultoportule also

has two satellite pores (Figure 2-13).

Diagnosis: In the light microscope, *C. siberica* can be difficult to differentiate from the other small *Cyclotella* species found in Buyantsog, described here as *Cyclotella buyantsogii*. It has a smaller size range and no features on the central valve face. The striae are short, leaving a wide unornamented central area. In contrast, at least one central pore is visible on *Cyclotella buyantsogii* and additional valve face decoration and undulation or the labiate process may be visible on some specimens. Marginal striae also tend to be longer in *C. buyantsogii*, resulting in a smaller central area. In the SEM, *C. siberica* has a labiate process on a marginal strut, while the labiate process in *C. buyantsogii* is farther out onto the internal valve face (Figure 2-13).

Distribution: *C. siberica* was found in only one of the 64 lakes surveyed, Buyantsog Nuur (described above), its first report in Mongolia from outside the Lake Hövsgöl region. It was previously reported in Mongolia from Lake Hövsgöl by many authors (e.g. Kozhova and Zagorenko 1976; Kozhova et al. 1977; Edlund et al. 2003, 2006). This small taxon was originally described by Skabitschevsky (1967) from plankton in the Tara and Irtiish Rivers, Omsk Region, Russia. Skabitschevsky (1967) indicated that valves are 4.5–7.5 µm diameter, bear short striae of 1/4 to 1/5 of valve radius at a density of 13–16 per 10 µm, and have a flat valve face. *Cyclotella sibirica* has also been reported in the planktonic flora of Lake Baikal (Bondarenko et al. 1993; Popovskaya 1993) but it is otherwise rarely recorded. Specimens from Buyantsog Nuur are similar to populations from Lake Hövsgöl (Edlund et al. 2003).

Discussion

The cyclotelloid diatoms are a common element of many planktonic floras, often have high and/or cryptic diversity within lakes (Tuji and Houki 2001; Edlund et al. 2003; Tanaka 2007), and individual taxa may occupy narrow ecological niches in freshwaters, which makes them excellent ecological indicators (Fritz et al. 1993; Wunsam et al. 1995; Julius 2000). Diverse groups are also known in brackish to saline sites (e.g. Prasad et al. 1990) and *Cyclotella* species are often key indicator species for paleosalinity in arid and semi-arid regions of the world (Fritz 1993; Gasse 2002).

It has been noted that in order to create and merge diatom-environment data sets, consistent taxonomy is required and that the small centric species are often problematic (Carvahalo et al. 1995; Wunsam et al. 1995; Cremer et al. 2001) This is partially due to their small size and difficulty in identifying diagnostic features in the light microscope, and partially due to a long-standing confusion and misinterpretation of original descriptions and nomenclature (e.g., Håkansson 1993; Håkansson et al. 1993). Focused taxonomic efforts help ensure that diatoms are a more powerful tool for understanding and monitoring the sensitive and important aquatic ecosystems in Mongolia.

In order to make comparisons between western Mongolia and other saline lake regions, and to enable the potential to merge calibration datasets in the future, a careful taxonomic study of this group was critical. We identified nine cyclotelloid diatoms from western Mongolia lakes. With detailed study, we distinguished two small *Cyclotella* species from Buyantsog Nuur, *C. siberica* and the new species *C. buyantsogii*, which were difficult to separate in the light microscope. We have also found that *C. choctawhatcheeana*, often used as an indicator of saline conditions, is morphologically the same species in Mongolia as in other saline environments (Carvalho et al. 1995). And importantly, we describe two new diatom species, *P. khyargusiana* and *C. uuregensis*, that apparently have endemic distributions limited to their type localities.

Within mid-Asia, the prevalence of endemism is highlighted by the ancient lakes. For example, of the nearly 500 diatom taxa reported from Russia's Lake Baikal, as many as one-third are endemic (Skvortzov & Meyer 1928; Skvortzov 1937; Levkov, submitted). Japan's Lake Biwa similarly has many endemic taxa (Tuji and Houki 2001; Ohtsuka and Tuji 2002). Intriguing examples of endemism have also been reported from Mongolia's ancient Lake Hösvgöl. In addition to endemic phytoplankton (Edlund et al. 2003; Pappas and Stoermer 2003), endemic lineages such as the *Navicula reinhardtii*-species flock presumably represent monophyletic groups decended from more widespread taxa (Edlund et al. 2006).

The major terminal basins of the Valley of the Great Lakes offer additional isolated and/or long-lived environments that appear to host endemic species. *Cyclotella uuregensis* is limited in distribution to Uureg Nuur, a closed basin lake of unknown geological history. *Puncticulata khyargusiana* was also identified from a single terminal lake basin, Khyargus Nuur. Both of these lakes are moderately saline, isolated from other similar lake types, and offer unique physical, biological, and limnological conditions that would be conducive to developing endemism (Dulmaa 1979; Gunin et al. 1994).

In addition to taxa that are limited in distribution to individual water bodies, the mid-Asian diatom flora also contains characteristic elements with broader distributions. For example, *Cyclotella siberica* is a a taxon that, although uncommonly reported, is widely distributed in mid-Asian rivers and lakes (Skabitschevsky 1967; Bondarenko et al. 1993; Edlund et al. 2003; this study). Similarly, *Cymbella stuxbergii* and several *Hannaea* taxa are widespread but characteristic of Asian waters (Williams et al. 1999; Bixby et al. in review).

Of particular biogeographical interest are the saline lakes of western Mongolia. They contain an intriguing mix of diatom taxa having widespread to narrow distributions. At one end of the spectrum are widespread taxa such as *Navicymbula pusilla*, and *Amphora coffeaeformis*, which can be found in many inland saline lakes and even marine collections worldwide, and are common in the saline lakes of the VOGL (Prasad et al. 1990; Edlund et al. 2001). Other species, such as *Cyclotella choctawhatcheeana*, are globally distributed (Carvalho et al. 1995) but surprisingly limited in the saline systems of western Mongolia. In addition to possibly endemic taxa such as *C. uuregensis* and *P. khyargusiana*, other taxa were limited in distribution to one one or two saline lakes; such as *Amphora soninkhishigae*, which was found only in Oigon Nuur and Uvs Nuur. Of the more than 300 diatom species identified in this survey across all genera, over 100 occurred in only a single lake, many of these occurrences were groups such as *Campylodiscus*, *Pinnularia*, and *Surirella*, and occurred in low abundances in a small number of samples. Further focused sampling of these saline habitats will lead to a more refined understanding of the distributions of diatoms in this unique region.

In addition to diatom biodiversity, Mongolian wetlands and inland lake systems have been identified as critically important regions for conservation of global biodiversity (Olson and Dinerstein 1998). Climate change, industrial development, and increased grazing pressure are known to be negatively impacting the quantity and quality of surface water in the region (Soninkhishig 1998; Stubblefield et al. 2005; Kelderman and Batima 2006; Shinneman et al. in press). Diatom distribution in Mongolia is strongly related to water chemistry and microhabitat (Edlund et al. 2001; Shinneman et al. in press) and diatoms have strong potential to be used as modern monitoring tools and as a proxy for paleo-environmental investigations (Shinneman et al. in press). Diatom studies have already been applied preliminarily as ecological indicators (Soninshishig 1998) and as paleolimnological tools (Dorofeyuk and Tarasov 1998; Peck et al. 2002; Fowell et al. 2003; Shinneman et al. in press) to assist in developing a baseline understanding of climate changes and ecological transitions in Mongolia.

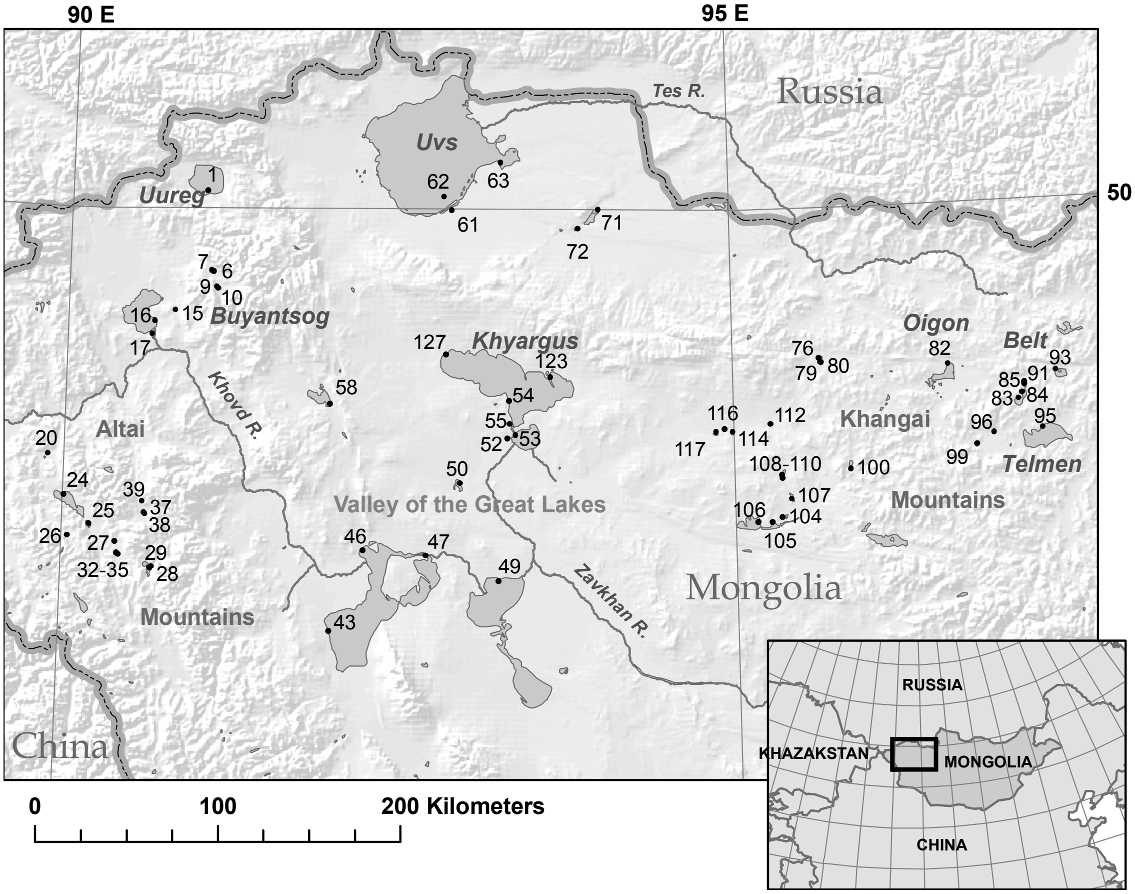


Figure 2-1: Valley of the Great Lakes and all sampling sites. Lakes discussed in detail in the text are labeled and include Uureg (Site 1), Buyantsog (Site 10), Khyargus (Sites 54, 123, and 127), Uvs (Sites 62 and 63), Oigon (Site 82), Belt (Site 93), and Telmen (Site 95).

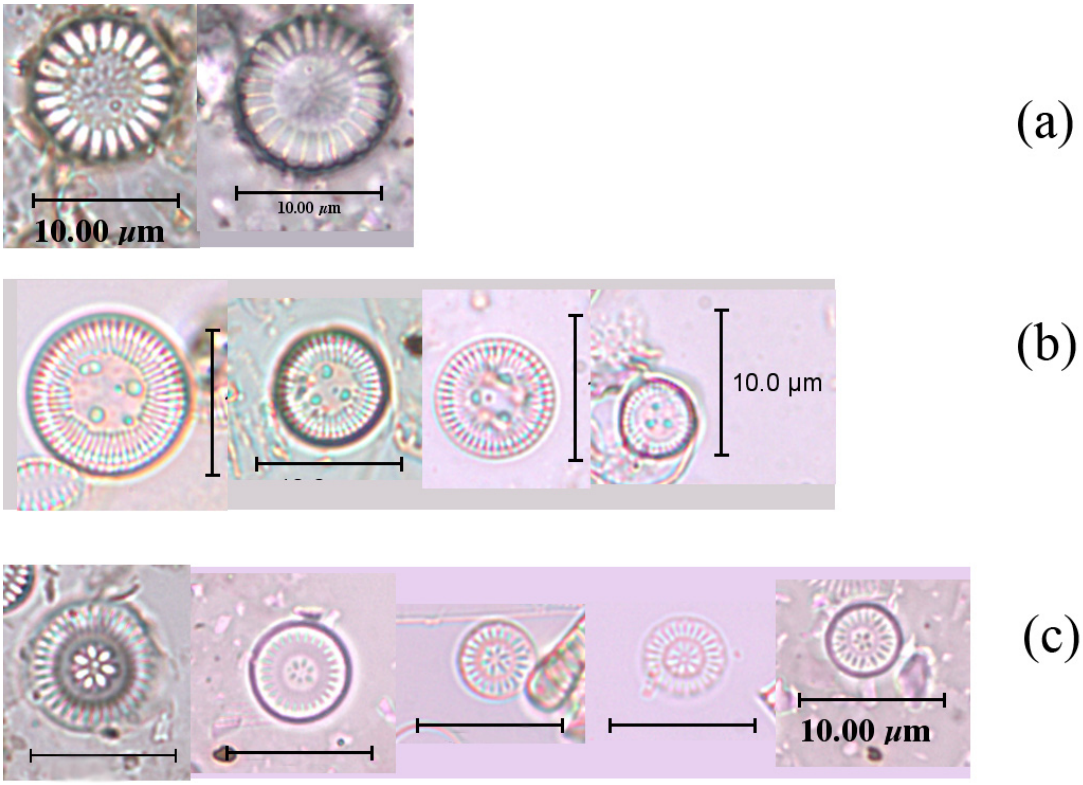


Fig. 2-2: Known and easily identified diatom from Western Mongolia (a) *Cyclotella meneghiniana* (b) *Cyclotella ocellata* (c) *Discostella pseudistelligera*

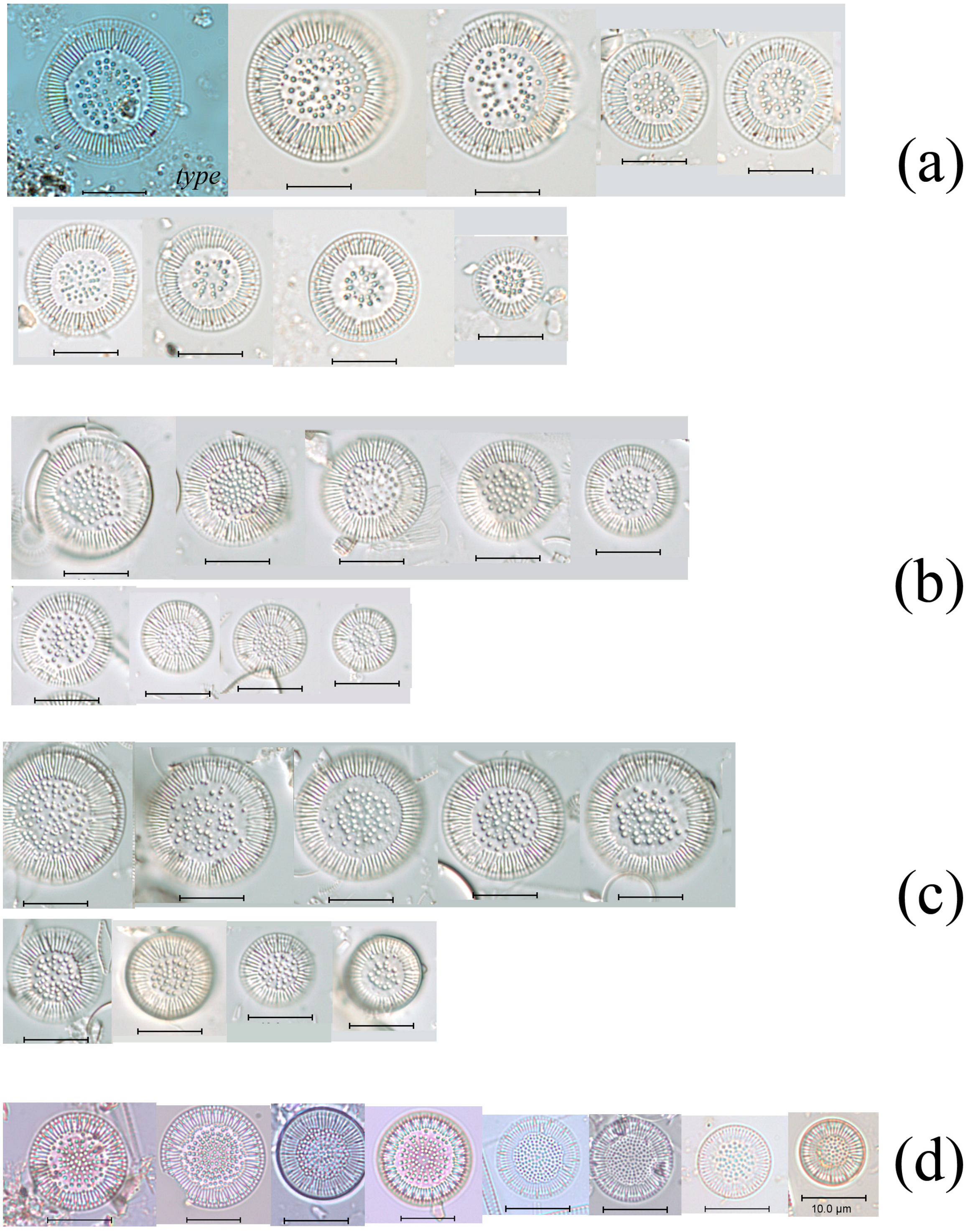


Fig. 2-3: Light micrographs of (a) *Puncticulata khyargusiana* (b) *P. radiosa* from Bust Lake (c) *P. radiosa* from Telmen Lake (d) *P. radiosa* from a variety of other lakes across western Mongolia. The type specimen is marked in (a). All scale bars are 10 microns.

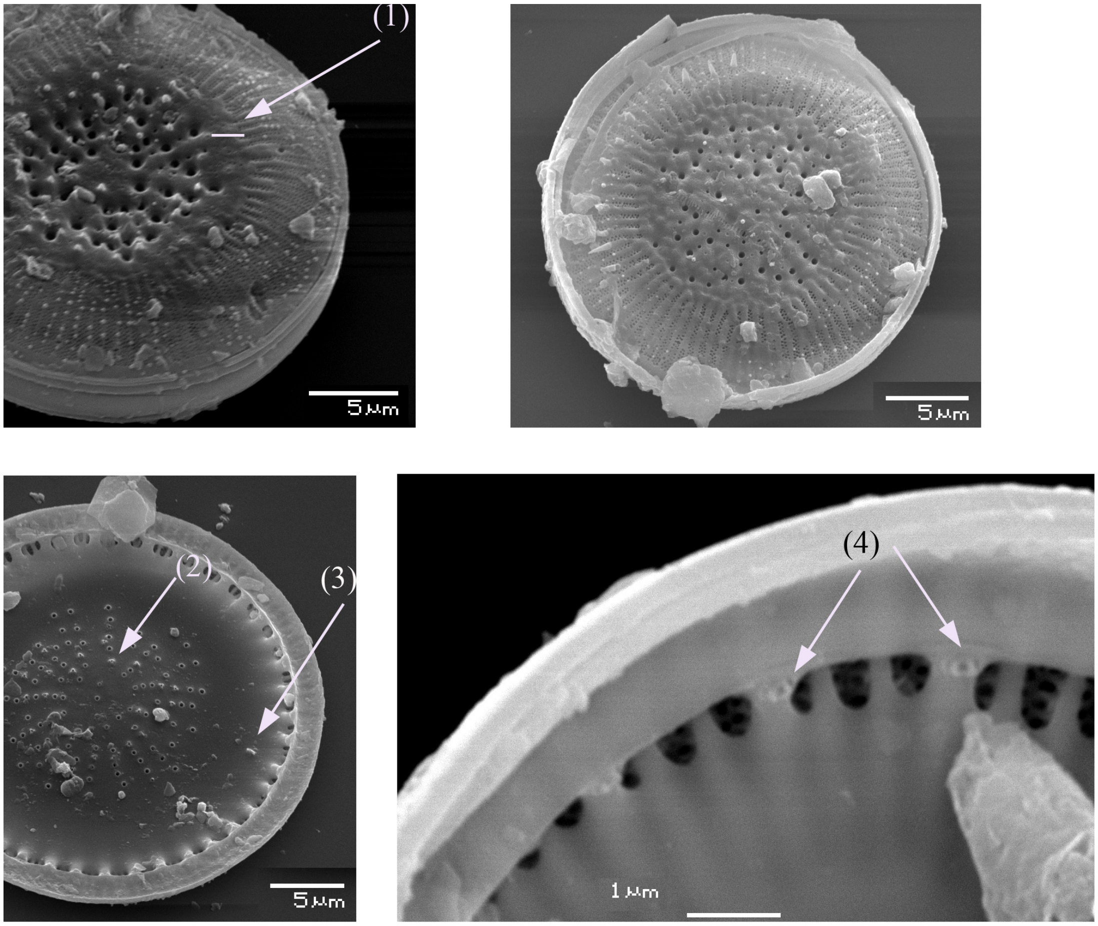
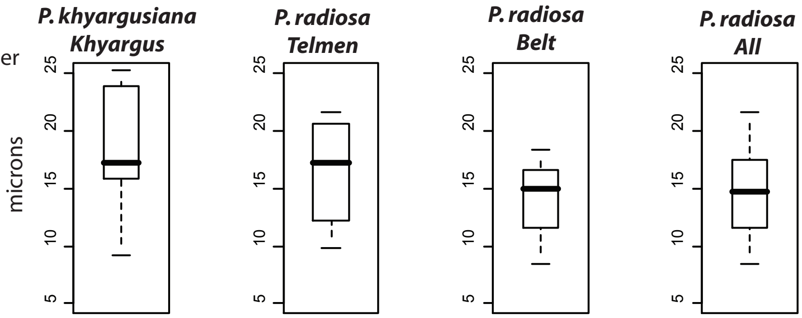
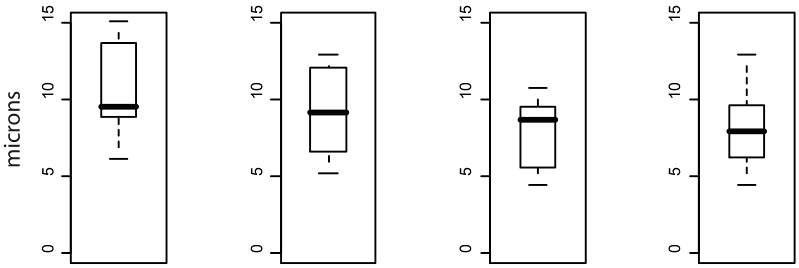


Fig. 2-4: Scanning electron micrographs of *P. khyargusiana* showing (1) the charateristic wide hyaline ring (2) the internal opening of the central fultoportulae with three satellite pores (3) the single labiate process and (4) the marginal fultoportulae with two satellite pores. SEM images are from paratype material (M786).

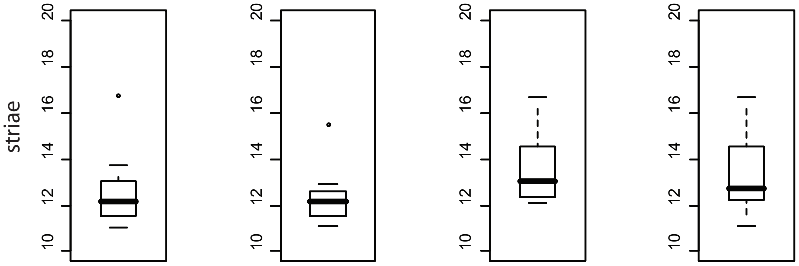
(a) Diameter



(b) Central Area Diameter



(c) Striae in ten microns



(d) Width of hyaline ring

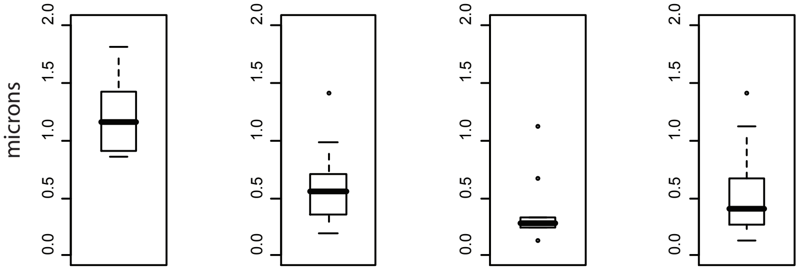


Fig. 2-5: Select morphological characteristics of *P. radiosa* in two large, saline lakes (Belt and Telmen) and the total distribution of *P. radiosa* compared with *P. khyargusiana*. Boxes surround the 25th to 75th percentiles, center line is the mean, lines extend to the complete range with points representing outliers. Diameter (a), central area diameter (b), and striae count (c) are not significantly different between the four distributions (Students t-test; $p>0.01$). The width of the hyaline ring (d) is, however, significantly ($p<0.005$) wider in *P. khyargusiana*.

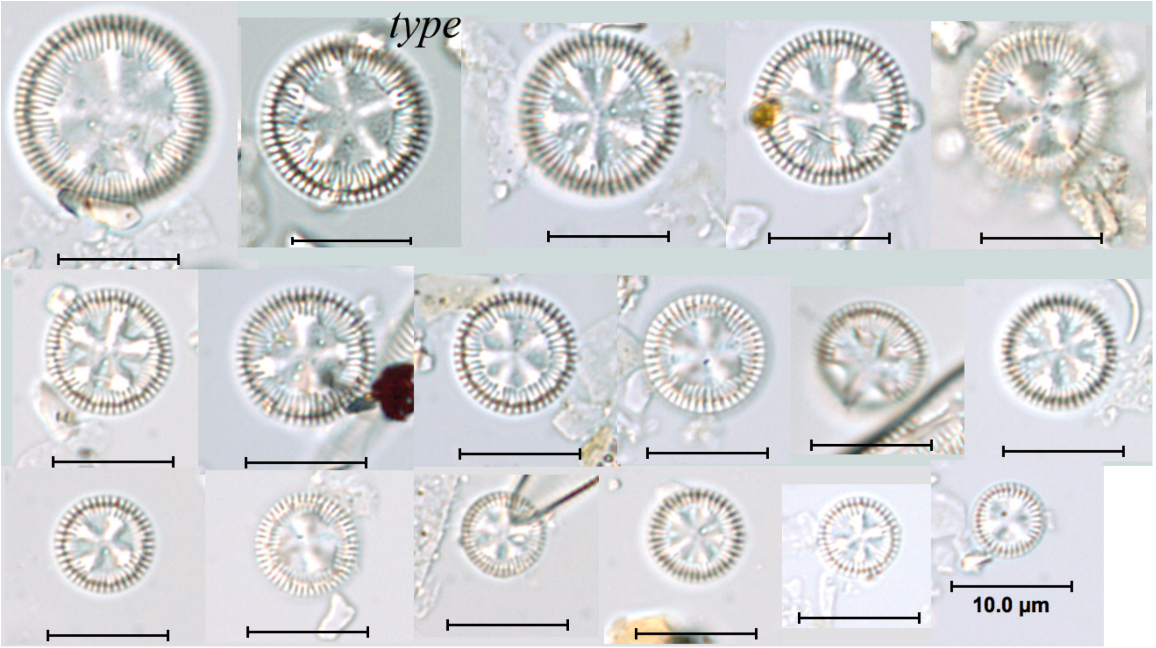


Figure 2-6: Light micrographs of *C. uuregensis*. Type specimen is indicated in upper row. Scale bar = 10 microns.

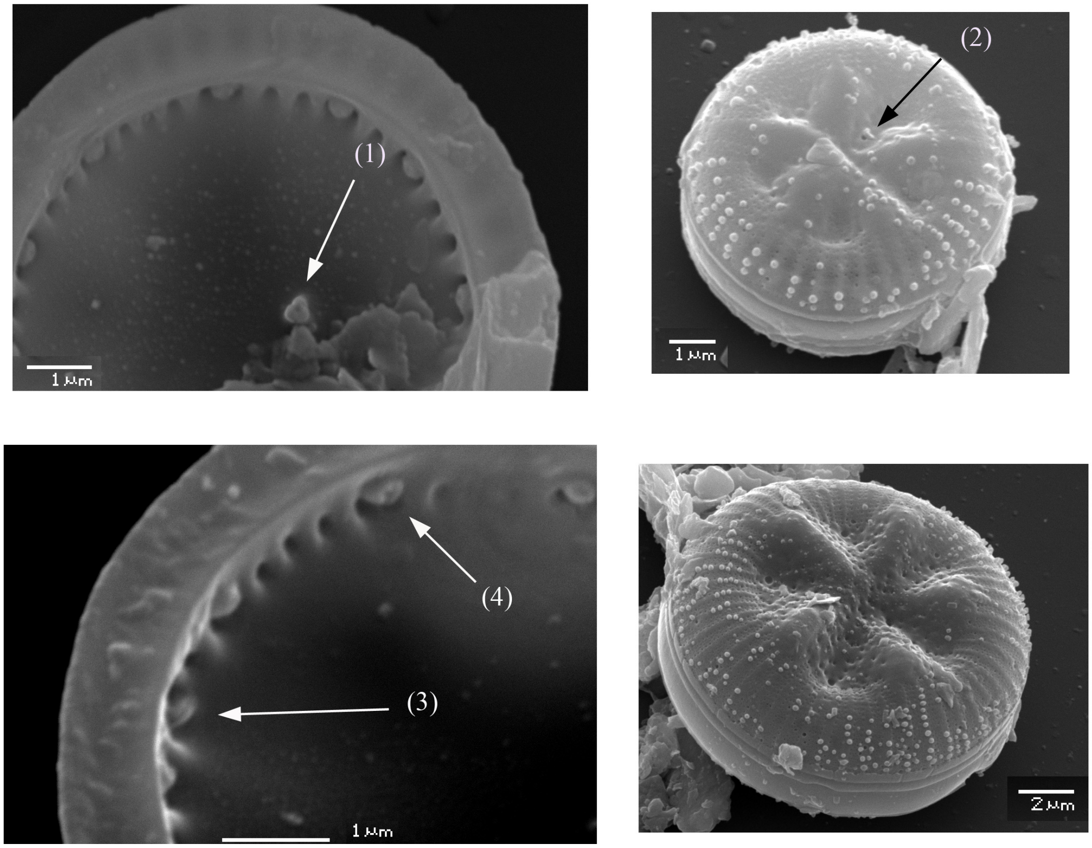


Figure 2-7: Scanning electron micrographs of *C. uuregensis* detailing (1) the internal opening of the central fultoportulae with its three satellite pores, (2) the external opening of the central fultoportulae (3) the position of the labiate process and (4) the marginal fultoportulae

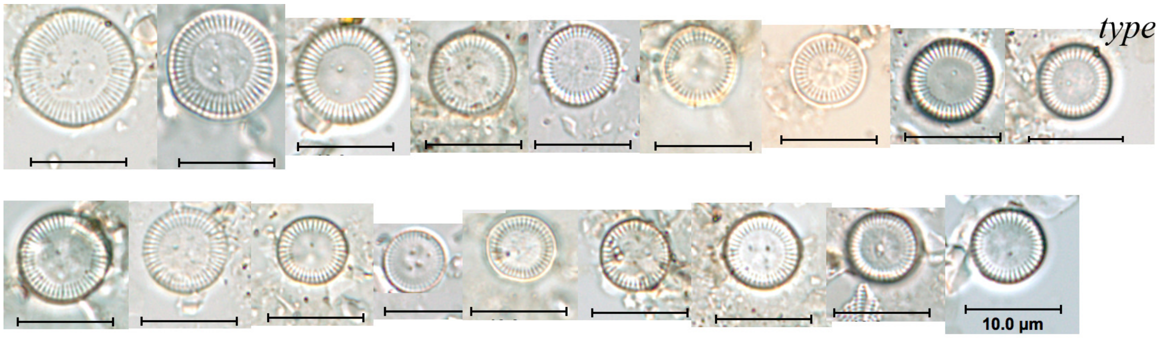


Fig. 2-8: Light micrographs of *Cyclotella buyantsogii.* Type specimen is indicated in upper row. Scale bar = 10 microns.

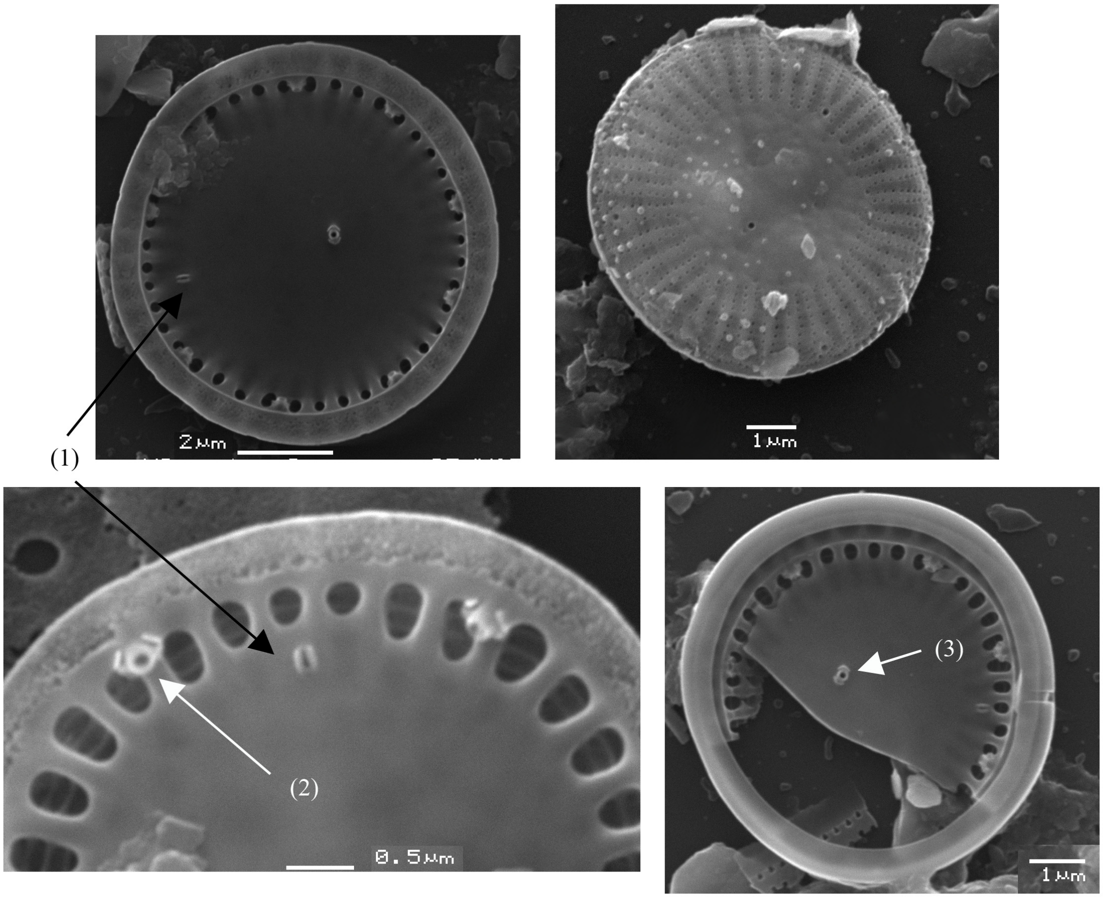


Figure 2-9: Scanning electron micrographs of internal and external views of *Cyclotella buyantsogii* showing (1) the location of the labiate process on the valve face (2) the marginal fultoportulae with two satellite pores and (3) the central fultoportulae with two satellite pores.

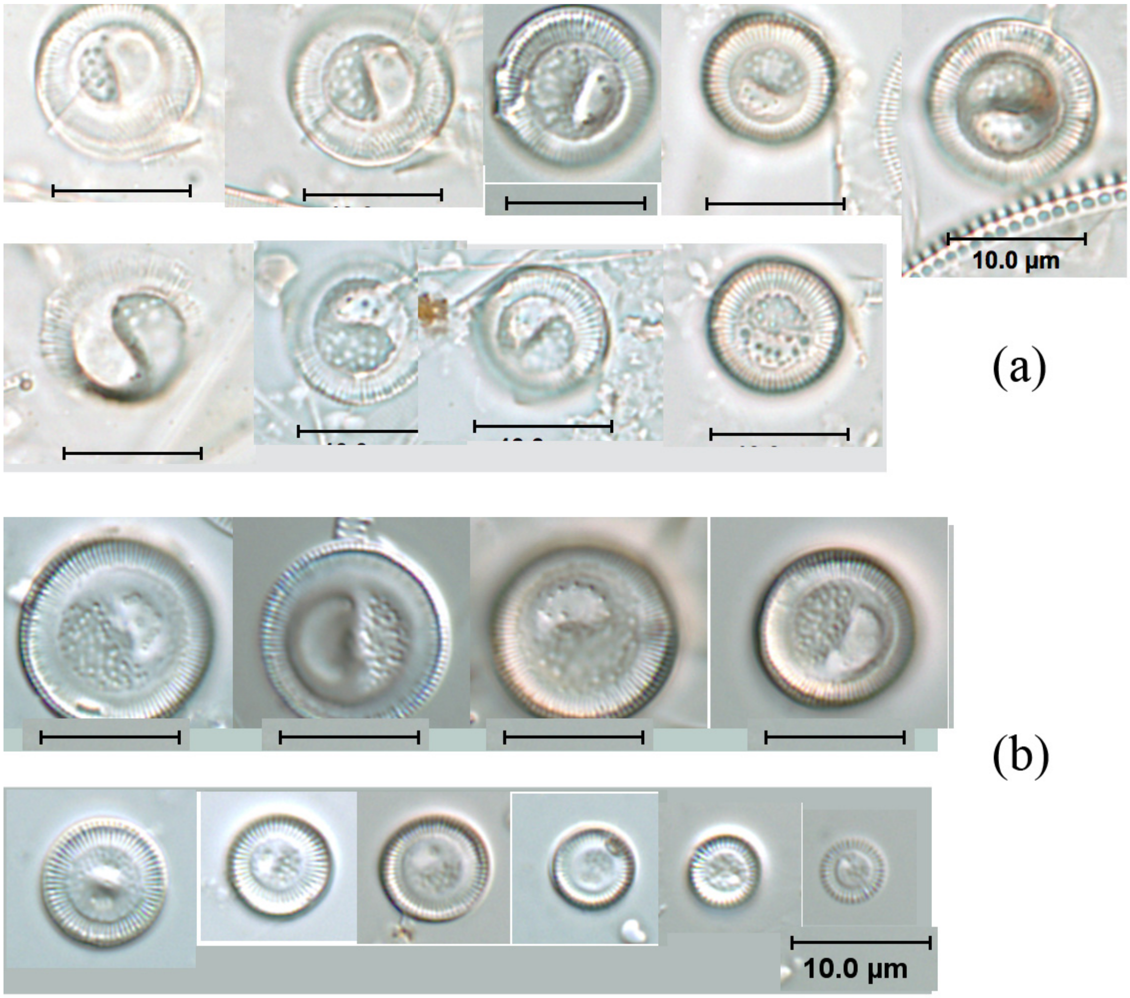


Figure 2-10 Light micrographs of *Cyclotella choctawhatcheeana* (a) from Oigon Lake and (b) from Uvs Lake. Scale bar = 10 microns.

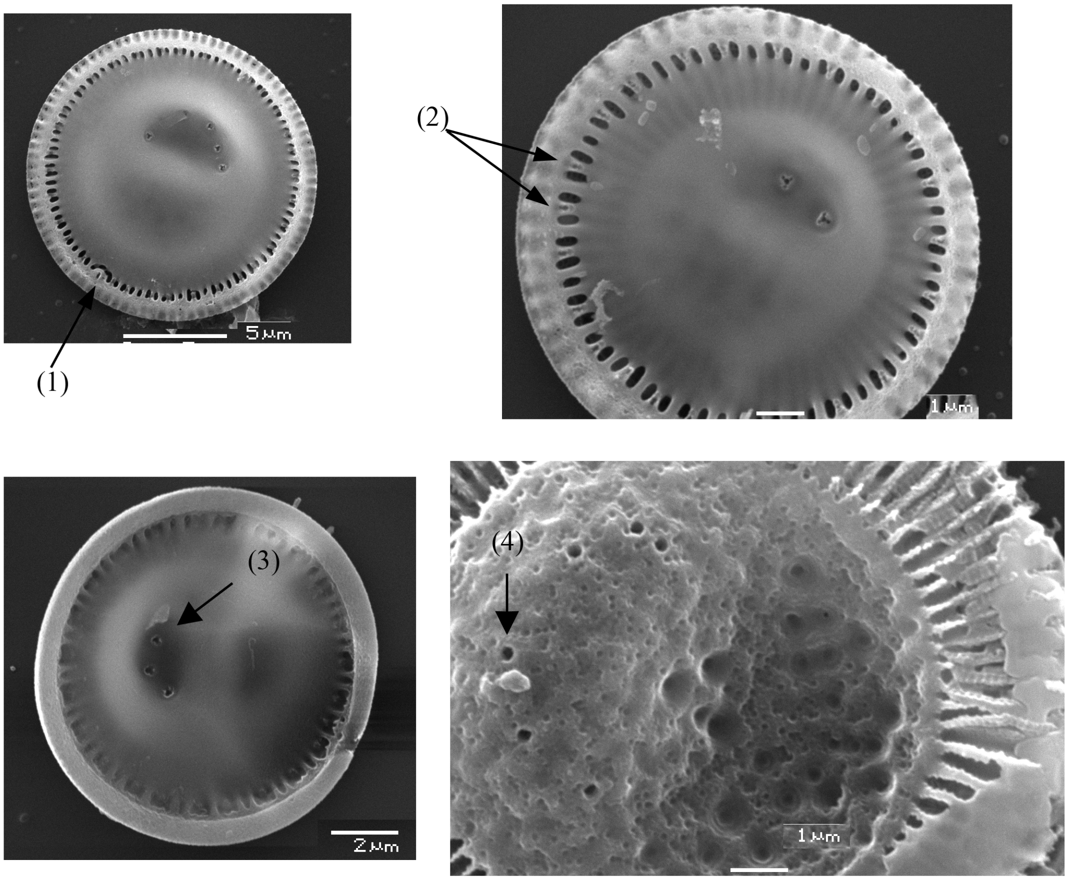


Figure 2-11: Scanning electron micrographs of *Cyclotella choctawhatcheeana* showing (1) the labiate process (2) the maginal fultoportulae with two satellite pores and the (3) internal and (4) external openings of the central fultoportulae

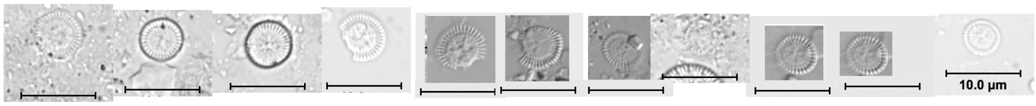


Figure 2-12: Light micrographs of *Cyclotella siberica*. Scale bar = 10 microns

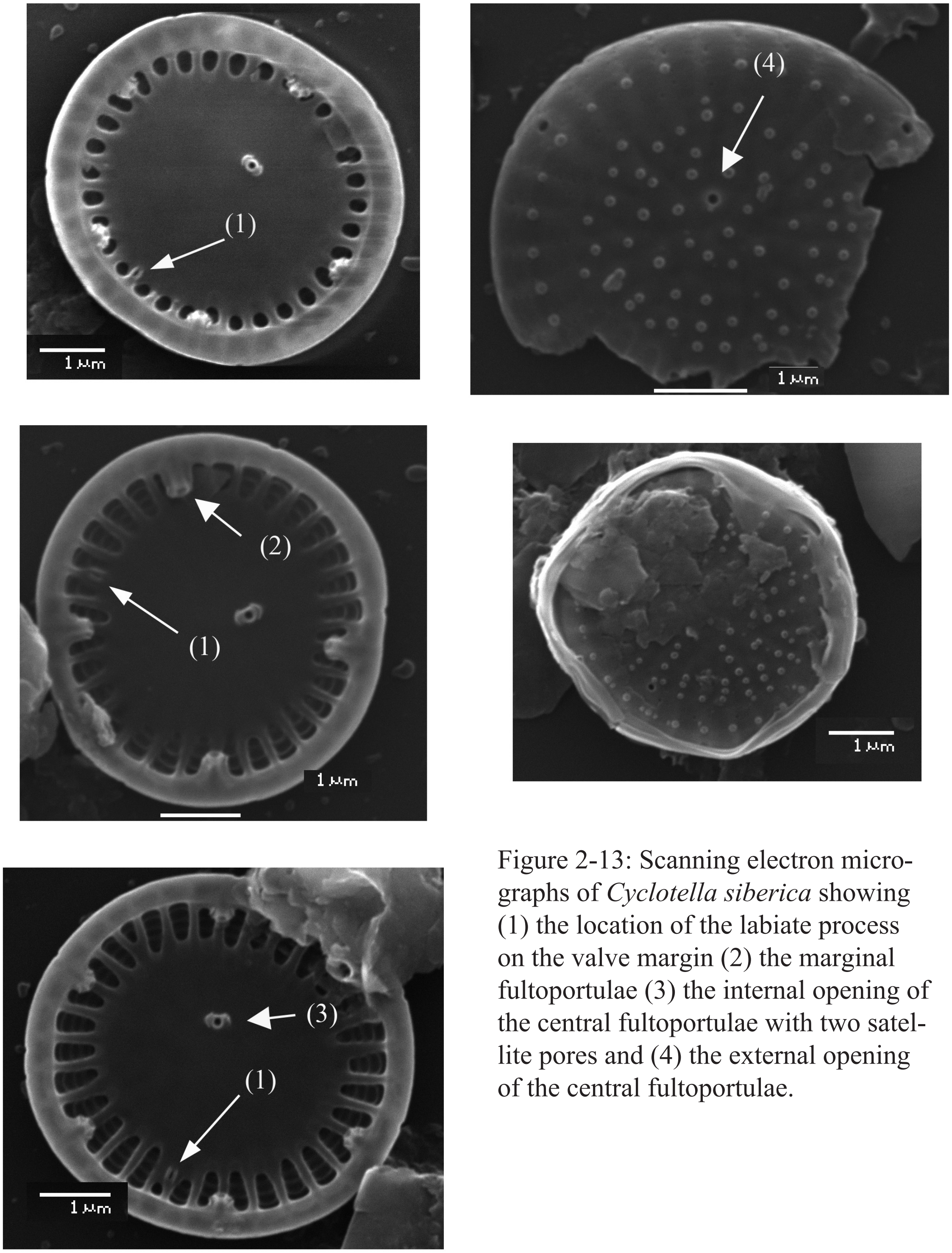


Figure 2-13: Scanning electron micrographs of *Cyclotella siberica* showing (1) the location of the labiate process on the valve margin (2) the marginal fultoportulae (3) the internal opening of the central fultoportulae with two satellite pores and (4) the external opening of the central fultoportulae.

Site code	Site #	Lat./Long. (decimal degree)	Elevation (m)	Lake type	SC (µS cm^{-1})	TP (mg L^{-1})	HCO$_3$ (mg L^{-1})
KHOLBO	6	49.7/91.2	2570	SS	69	0.145	41
OLONN2	7	49.7/91.1	2568	SS	78	0.035	45
BARSAL	9	49.6/91.1	2530	SS	357	0.058	145
BUYANT	10	49.6/91.1	2553	SD	319	0.014	174
BAGANR	15	49.5/90.8	1547	SS	7050	0.461	933
ACHITN	16	49.4/90.7	1438	LS	328	0.026	152
ZUUNKH	17	49.4/90.6	1437	LS	383	0.04	185
TOLBON	24	48.6/90.0	2079	LD	951	0.02	509
JJTOLB	25	48.2/90.2	2089	SS	216	0.069	78
ALKHAR	26	48.4/90.6	2510	LD	41	0.015	23
ALALTN	27	48.4/90.4	2211	SS	225	0.123	116
JJDORO	28	48.2/90.7	2394	SD	7500	0.328	264
DOROON	29	48.2/90.6	2394	LD	4543	0.159	314
XOXNR1	32	48.3/90.4	2232	SS	2200	0.056	222
XOXNR2	33	48.3/90.4	2228	SS	3000	0.113	449
XOXNR3	34	48.3/90.4	2225	SS	7900	0.194	751
XOXNR4	35	48.3/90.4	2223	SS	1530	0.071	271
ZAGASN	37	48.5/90.6	2376	SD	473	0.062	184
ARALNR	38	48.5/90.6	2375	SS	489	0.122	174
KHAGNR	39	48.6/90.6	2426	LS	282	0.045	149
KHRUSS	43	47.9/92.0	1157	LD	197	0.071	85
KHRUSN	46	48.3/92.2	1157	LD	120	0.023	72
DALAIN	47	48.3/92.7	1156	LS	161	0.022	86
KHARNR	49	48.2/93.2	1132	LS	262	0.027	138
ZOSTNR	52	48.9/93.3	1032	SS	404	0.34	132
AIRAGN	53	48.9/93.4	1030	TVL	4350	0.024	1315
KHYARG*	54	49.1/93.3	1028	TVL	8610	0.027	2112
SHUVUU	55	49.0/93.3	1019	SS	10300	0.148	5939
UVBAGA	61	50.0/92.9	759	SD	26391	0.105	883
UVSNRS	62	50.1/93.3	759	TVL	20682	0.016	777
UVSNRE	63	50.3/93.3	759	TVL	20363	0.023	1474
BAYANR	71	50.0/94.0	981	LD	465	0.007	224
DNBAGA	72	49.9/93.8	981	SD	977	0.068	295
TSVPD1*	78	49.3/95.6	1635	SS	1040	0.763	239
TSVPD2	79	49.2/95.7	1622	SS	1740	0.492	175
TSVPD3	80	49.2/95.7	1650	SS	15325	0.082	1243
OIGONR	82	49.2/96.6	1680	LD	32276	0.058	1055
KHOLB2	83	49.0/97.1	1940	SD	2772	0.052	654
ULAANR	84	49.1/97.2	1935	LS	1990	0.18	431
KHUNTN	85	49.0/97.2	1939	SD	2958	0.042	667
TSETNR	91	49.1/97.2	1933	LS	771	0.151	272
BELTLK	93	49.2/97.4	2040	LD	3252	0.028	828
TELMEN	95	48.9/97.3	1789	LD	8630	0.017	1096
YALAAT	96	48.9/96.9	1824	SS	220	0.036	108
TAKILT	99	48.8/96.8	1841	SD	3370	0.041	473
TSEGEN	100	48.7/95.9	1882	SS	12430	0.196	667
TSGNPL	102	48.7/95.9	1882	SS	25500	1.363	835
GASHUN	104	48.4/95.3	1520	LS	3300	0.115	748
KHUNT2	105	48.5/95.3	1505	SS	250	0.03	117
DBAYAN	106	48.5/95.1	1481	LD	370	0.011	216
KHOLB3	107	48.6/95.4	1560	SS	296	0.058	96
DEVPD1*	109	48.7/95.3	1540	SS	42900	2.635	2560
TSAGN1	112	48.9/95.3	1458	SS	29083	0.037	523
OLGOIN	116	48.9/94.9	1382	LS	8550	0.296	875
TSAGN2	117	48.9/94.9	1370	SD	12830	0.104	518
KHYAR2	123	49.2/93.6	1028	TVL	9450	0.02	1476
KHYAR3	127	49.3/92.8	1028	TVL	9400	0.031	1470

* These lakes were removed from the final calibration set (Shinneman et al. in press)

Table 2-1: Select environmental data for lakes surveyed

	# of lakes	TP range (mg L^{-1})	SC range (µS cm^{-1})	calculated TP optima (mg L^{-1})	calculated SC optima (µS cm^{-1})
Cyclotella buyantsogii	1	0.014	319	0.014	322
Cyclotella choctawhatcheeana	2	0.023-0.058	20,682-32,276	0.060	30909
Cyclotella meneghiniana	3	0.082-0.34	404-15, 325	…	…
Cyclotella ocellata	5	0.007-0.04	262-951	0.010	432
Cyclotella siberica	1	0.014	319	0.091	4096
Cyclotella uuregensis	1	0.08-0.01	6100	…	…
Discostella stelligera	9	0.007-0.145	69-3252	0.032	2812
Puncticulata khyargusiana	1	0.020-0.031	8610-9450	0.020	9450
Puncticulata radiosa	27	.007-.330	69-8630	0.042	2277

Table 2-2: All 9 cyclotelloid species encountered in western Mongolia with information on distribution and environemntal ranges. Not all species occured in sufficient abundance to be used in the calibration set.

Chapter 3

Paleolimnologic evidence for recent eutrophication in the Valley of the Great Lakes (Mongolia)

Abstract

Climate warming and major land use changes have profoundly affected the Mongolian landscape in the past several decades. Previous studies have recognized the impact of a warmer, more arid climate and Mongolia's 1991 transition from command to market economy on terrestrial ecosystems, including impaired sustainability of subsistence herding and threats to wild animals. Here we examine the impacts of changed herding practices and climate warming on aquatic systems and find the combined effects of climate and land use changes are leading to an increased nutrient flux to regional lakes.

Water quality measurements taken in 2004 and 2005 indicated many lakes in western Mongolia had reached levels of nuisance eutrophication. Diatom-based models for total phosphorus along with records of loss-on-ignition, sediment accumulation rates, diatom community structure, biogenic silica and phosphorus fluxes from five sediment cores show modern nutrient concentrations (0.03-0.07 mg L^{-1} total phosphorus) are at the highest levels observed in the last century. Longer records of biogenic silica, sediment phosphorus, and diatom planktonic to benthic ratios show these recent increases in productivity are unique in Mongolian history. The trend toward increasing nutrient concentrations is recent and temporally linked with changes in grazing patterns and intensity as well as with warmer than average temperatures. Variance partitioning analysis demonstrated that the combined effects of increased animal population and climate warming contributed to the recent eutrophication. The results presented here demonstrate a need for further study and long-term monitoring of water quality in Mongolia.

Introduction

The arid plateaus of Central Asia comprise a unique environment, isolated from surrounding regions by mountains and desert. These high elevation mid-latitudes have been strongly affected by recent warming, experiencing increases in average annual temperature of 1.8º C over the past 60 years, more than twice the global average (Batima 2006). At the same time, rapid economic and political transitions in the region have led to changing land use with little regulation.

About half of the Mongolian population remains directly engaged in traditional semi-nomadic or transhumant pastoralism, which has a history of at least 4000 years in the Central Asian grasslands. Approximately one-third of the population relies on herding as a primary source of livelihood (World Bank 2006). Since the departure of the Soviet government in 1991, the central planning of migrations has been abolished. In the early 1990s, all resources belonging to the collectives were returned or partitioned to individual families (Sneath 1999). Today families are responsible for planning and carrying out their own migrations as well as for securing provisions formerly provided or subsidized by the State or other governing body. This de-regulation has drastically altered historical land-use norms, with herders increasing herd sizes and decreasing their mobility on the landscape, often concentrating grazing in smaller areas near towns and villages, without the resources to carry out longer and more frequent migrations (Fernández-Giménez 2002; Mearns 2004).

Mongolia is home to several unique and endangered habitats (Olson and Dinerstein 1998) as well as an important stopover point for migratory birds (Brinson and Malvárez 2002); hence the need to understand broad-scale ecosystem health in this region in the face of changing climate and an unstable economy is easily recognized. Previous research has identified the toll that recent climate and land-use changes have had on grazing lands, domestic herds, and wild animal populations in Mongolia (Pratt et al. 2004; Maroney 2005).

In contrast, research on water resources has been limited largely to the impacts of urban growth, mining and other industrial processes on river systems (Soninkhishig 1998; Stubblefield et al. 2005; Kelderman and Batima 2006) with little attention to lakes or aquatic systems as a whole. A United Nations water and sanitation report for 2004 indicated only 30% of people in rural Mongolia had access to an improved water source; the remainder relied on natural sources including springs, rivers, and lakes making the conservation of surface waters critically important (Batbold et al. 2004). Eutrophication leads to a wide variety of deleterious conditions, including toxic algal blooms, changes in macrophyte floras, fish kills, and loss of biodiversity (Bennett et al. 2001). In Mongolia, several of these problems are of particular concern given the dependence of the economy on natural resources as well as the country's ecological importance in Central Asia.

Western Mongolia has little to no agricultural land and therefore no excess phosphorus inputs from fertilizer. Industrial point sources, such as wastewater treatment facilities, are also largely absent in the region. Our water quality survey in 2004 and 2005 revealed, however, that many lakes were highly eutrophic. In the absence of long-term monitoring data, the timing, duration, and causes of the impaired status of these lakes was unknown. Increased livestock populations and increasingly concentrated grazing in small areas has been demonstrated to be detrimental to terrestrial vegetation and soil health in surrounding regions (e.g. Li et al. 2008) but no evaluation of the impacts on aquatic systems have been conducted.

In response we developed a diatom-based calibration set (Shinneman et al. in press) and applied it to sediment cores from five lakes in western Mongolia to reconstruct lake-water total phosphorus. These records, in addition to those of loss-on-ignition, phosphorus and biogenic silica in the sediment, have been used to reconstruct the nutrient status of these lakes over the past approximately 120 years. Our results showed some increases in nutrient concentrations coincident with rising mean annual temperatures in the 1980s and 1990s followed by more rapid increases in inferred nutrient concentrations following the 1991 transition to a free-market economy. Evidence for recent eutrophication was greatest in lakes near population centers and less pronounced in more remote areas. Longer records demonstrated that, while in-lake productivity varied over time, recent trends are outside the normal range of variability.

Study Region

The Valley of the Great Lakes lies in far western Mongolia, bounded by the Altai Mountains to the west, the Khangai Mountains to the east, and the Gobi Desert to the south (Figure 3-1). The Great Lakes region is part of the internally drained Central Asian Basin; it includes several smaller closed-drainage basins with lakes ranging from fresh to hypersaline (Dulmaa 1979; Table 3-1). Many of the large terminal basins in the valley are believed to be the remnants of large Tertiary or Quaternary paleo-lakes (Grunert et al. 2000).

Local climate is harsh; the average annual temperature is near 0ºC, with long, cold winter months punctuated by hot, dry summers. Average annual rainfall is variable, with the most arid conditions (<100 mm/yr) in the valley bottom and slightly wetter conditions (300-400 mm/yr) in the Khangai Mountains to the east (Academy of Sciences MPR, 1990). The western part of the country is distant from the increasingly industrial and service-driven economy of the capital city of Ulaanbaatar and the economy of the region relies heavily on a pastoral tradition for both subsistence and income.

Methods

Climate and Grazing Records

Six weather stations in Western Mongolia (Hovd, Omno-Gobi, Altai, Baruunturuun, Tosontsengel, Uliastay) are part of the publicly available Global Historical Climate Network (KNMI 2007). These stations have semi-continuous records of temperature and precipitation varying from 44 (Tosontsengel) to 70 (Hovd) years in length. Stations were located across the region (Fig 3-1) and varied from 1232 m (Baruunturuun) to 2181 m (Altai) in elevation; in order to make the records more comparable, each was standardized by subtracting the average series value from each data point and dividing by the standard deviation within that station record. Seasonal temperature and precipitation series were developed by averaging monthly anomalies at each station to produce summer (June, July, and August) and winter (December, January, and February) means for each year. Years that were missing data for more than one month per season were not used.

In order to use all station data as a regional climate record, and to create a more continuous time series from discontinuous individual stations, results are presented as the composite average deviation from the mean for all six stations. Individual records do not vary substantially from the composite for the temperature records; precipitation is more variable among the individual stations (Figure 3-2). Local grazing records were not publicly available; national herd size from previously published records (Bold 1998; World Bank 2003; FAO 2007) was assumed to be proportional to local herd size.

Water chemistry

Pelagic water samples were collected during August 2004 and 2005 from inflatable canoes. For small lakes the sample site was the deepest part of the lake, measured with a hand-held acoustic depth meter. For larger lakes the sample site was well off shore at the deepest point reached, up to a depth of about 30 m. Field variables (temperature, specific conductance, pH, and dissolved oxygen) were measured with a Yellow Springs Instruments (YSI) multi-parameter water-quality sonde. Epilimnetic samples were collected by hand at a depth of 30 cm in 500-mL amber high-density polyethylene (HDPE) field bottles rinsed three times with sample water. Most lakes had only one pelagic sampling site; exceptions were the large lakes Uvs Nuur (two sites) and Khyargas Nuur (three sites). Where emergent vegetation was prevalent, a littoral zone water sample was also collected at 30 cm depth. In stratified lakes, hypolimnetic samples were collected with a Kemmerer water sampler. Field samples were split at the end of each day into subsamples for further analyses. Twenty mL of unfiltered water were poured into 60-mL HDPE bottles for total phosphorus (TP) and total nitrogen (TN) analyses. All other subsamples were filtered through a 0.45-µm low-extractable membrane filters attached to a 60-mL syringe, which had been rinsed with 30 mL of sample water. Total phosphorus and total nitrogen were determined on a Lachat QuikChem 8000 Flow Injection Analysis Autoanalyzer. Alkaline persulfate dual digestion of TP and TN subsamples (modified from Ameel et al. 1993) was performed in the 60-mL HDPE field bottle to preclude adsorptive loss of nutrients to the bottle wall. Trophic state index (TSI) for each lake was calculated according to Carlson (1977).

Sediment Cores

Sediment cores were obtained from five lakes (Figure 3-1) using a polycarbonate tube fitted with a piston and operated by rigid drive rods. Coring sites were selected in lakes with relatively simple basin morphology where a deep, flat region was easily identifiable with a hand-held acoustic depth finder. Zagas and Kholboo lakes were located at high elevations in the Altai Mountains. Kholboo was a small, shallow lake and Zagas was a small lake with two deep basins separated by a shallow sill. Kholboo was located within a government Protected Area where some limits on grazing exist, though the degree of enforcement is undocumented. Baga was a small, shallow lake surrounded by sand dunes at relatively low elevation on the eastern edge of the Valley of the Great Lakes. Takhilt and Bayan lakes were located on the western flanks of the Khangai Mountains; both were relatively large and deep. Baga and Takhilt lakes were the nearest to modern town centers.

Each core was extruded in the field at 1-cm intervals and stored in airtight polypropylene vials for later analysis. In the laboratory, samples were homogenized and subsampled for further analysis. Loss-on-ignition was conducted according to Dean (1974). Age-depth models for the nine sediment cores were based on a combination of ^{210}Pb-dating and AMS-^{14}C dating of charcoal (Dr. Tom Brown, Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory). ^{210}Pb was measured through its grand-daughter product ^{210}Po (Eakins and Morrison 1978) and the constant rate of supply (c.r.s.) model (Appleby 2001) was used to estimate age. Charcoal for AMS-^{14}C dating was picked from the sediment and then treated with an acid-base-acid rinse. A range of 1-3 AMS dates were obtained for each core with the number of dates constrained by the availability of charcoal and maximum estimated age of the core.

AMS-^{14}C dates were calibrated using CALIB 5.0 (Stuiver and Reimer 1993; Stuiver et al. 1999). Age-depth models were constructed using linear interpolation or exponential models for the ^{210}Pb dates and either linear interpolation or linear fits for the older portions of each core. All dates are given as calibrated calendar years AD.

Carbon and nitrogen content of acidified (24 hrs in 1N HCL followed by 4-6 rinses) and then freeze-dried sediment was determined using a Costech Instruments 4010 Element Analyzer. Carbon-to-nitrogen ratios are reported as a molar ratio. Where sediment was available, phosphorus was measured at the same depth intervals as biogenic silica. Total phosphorus was extracted from samples with a combination of 30% H_2O_2 and 2.5 N HCl. A Lachat Flow Injection Analyzer was used to analyze the extracts colorimetrically (Liao 2002). Biogenic silica was extracted from approximately 30-mg samples of freeze-dried sediment with a 1% solution of Na_2CO_3 (Conley and Schelske 1993). Concentrations were measured colorimetrically (McKnight 2000) using autoanalysis (Lachat Instruments, Milwaukee, WI, USA). Estimates of percentage of silica were based on the average (or intercept) of 3, 4 and 5-h extracts as described by Conley (1998).

Diatom Analysis

Sediment for diatom analysis was first cleaned with 10% hydrochloric acid to dissolve carbonates. Samples were then heated in an 85° C water bath with a 30% hydrogen peroxide solution for at least three hours to oxidize organic matter, then centrifuged and rinsed (Renberg 1990). Cleaned material was settled on a cover slip and allowed to dry overnight in ambient conditions. Cover slips were mounted on glass slides using Naphrax or Zrax mounting media. Slides were counted on an Olympus BX-50 microscope at 1000x magnification under oil immersion. Counting followed the methodology of Ramstack et al. (2003), with 400 valves counted per slide in the uppermost sample, and 300 valves counted for each down-core sample. Specimens were included in a count when greater than 50% of the valve was present. Standard taxonomic references (e.g. Patrick and Reimer 1966; Krammer and Lange-Bertalot 1986-1991) as well as regional and species-specific primary literature (e.g. Cumming et al. 1995; Nagumo 2003) were used for species identification. Each taxon was photographed with a SPOT Insight QE camera attached to the microscope and images were maintained in a photographic database to ensure consistent identification among lakes. All diatom taxa counts were converted to percent abundance (relative to total diatom counts) for analysis. Quantitative sampling was not conducted; however, the abundance of diatoms can be estimated by the concentration of biogenic silica in the sediments (Conley and Shelske 2001).

Statistical Analyses

Multi-variate ordinations were used to explore relationships among physical and chemical gradients in lakes and their diatom species assemblages. All ordination analyses were run in R software with rare species downweighted before analysis using default functions in the vegan package of R (R Development Core Team 2006).

Four variables (specific conductance, total phosphorus, bicarbonate, and lake morphology) were identified as statistically significant and independent controls on the distribution of diatoms in regional lakes. These relationships were used to develop a transfer function for total phosphorus (TP) (Shinneman et al. in press). The model was developed and the predictive ability assessed using a weighted-averaging approach with bootstrap error estimation in C^2 software (version 1.4; Juggins 2003). The strength of the model was assessed with the coefficient of determination (r^2=0.74) and the root mean square error (RMSE for log TP=0.23). Because the same data are used to generate and evaluate the model, the RMSE is not entirely independent and the validation step of bootstrapping with 1000 cycles was used to generate a root mean square error of prediction (RMSEP for log TP=0.40) which more realistically portrays error estimates (Fritz et al. 1999). In order to ensure fossil diatom assemblages had good analogues in the modern calibration set, the similarity between fossil and surface samples was assessed using the squared chord distance coefficient in the analogue package of R (R Development Core Team 2006).

Correspondence analysis (CA) and a ratio of planktonic to benthic species were used to assess degree of floristic change between samples in a core. Constrained correspondence analysis (CCA) and partial CCA (pCCA) were used to examine relationships among diatom assemblages in core samples and possible explanatory variables, in this case, instrumental climate records and livestock population records, with the goal of partitioning the variance among these possible drivers (Lotter 1998; Hall et al. 1999). For variance partitioning in each core, the seven-year running means of climate and livestock population data were compared to changes in diatom assemblages. The running mean was used in order to capture the average condition for the years leading up to the time of sediment deposition and to smooth the inter-annual variability in climate. Seven years was the average time integrated in a sediment sample; five and ten year running means were also compared and gave similar results. These analyses included only samples from the period of instrumental record, extending back to 1938. A series of partial ordinations with each significant variable alone and each significant variable with other significant variables included as conditional co-variables was used to assess the unique and independent explanatory power of each variable.

Results

Grazing History and Climate Changes

Changes in climate and grazing practices have both significantly affected Mongolia in the last two decades. During a brief free market period between the end of the Chinese ‘neo-feudal’ system in 1918 and the establishment of socialist collectivism in the 1940s the number of livestock rapidly climbed from less than 10 million to over 25 million (Bold 1998; Figure 3-3). During the fifty years of collectivism (1940-1990), the total number of livestock in Mongolia was maintained between 20 and 25 million. In the post-Soviet era, the number of livestock has increased dramatically to more than 30 million animals (Figure 3-3).

A series of dry summers followed by winters with heavy snowfall, a natural disaster known as *dzud* in Mongolia, affected the country from 1999-2003 (Figure 3-2) and resulted in severe livestock losses, decreasing the national herd size by approximately 10 million animals (Figure 3-3). Since 2003 herders have been increasing herd sizes again in response to a need to increase food security (FAO 2007) and a desire for cash income from cashmere sales (World Bank 2003). As a result national herd size has rebounded to record levels.

In addition to short term fluctuations such as *dzud* events, Mongolia has experienced a warming of climate over the last several decades. Since about 1980, both winter and summer temperatures have been rising (Figure 3-2). Winter and summer precipitation were highly variable over the period of record but showed no clear trends.

Water quality and trophic status

Total nitrogen (TN), total phosphorus (TP), and trophic state index (TSI) indicated that most lakes, fresh and saline, were eutrophic to hyper-eutrophic at the time of sampling in late summer 2004 and 2005 (Figure 3-4). Modern total phosphorus values averaged 0.18 mgL^{-1} (range 0.007 mg L^{-1} to over 2 mg L^{-1}), well above nutrient concentration standards for most parts of the world. The Mongolian government has established some nutrient standards (Banzragch and Dorjsuren 2006) and new standards and updates were planned as a part of the 1994 Law on Water; however, such standards have not yet been made publicly available (Purevdorj Surenkhorloo, National Water Committee, Government of Mongolia, personal communication, 2007). Using the 0.02 mg L^{-1} TP standard defining impaired status from the United States Environmental Protection Agency region IV (Central Plains and Grasslands; E.P.A. 2001), 29 of 31 saline lakes and all but four of the 34 freshwater lakes had impaired status at either eutrophic or hyper-eutrophic levels (Table 3-1, Figure 3-4). Nitrogen to phosphorus ratios showed that most systems were strongly P-limited (Table 3-1, Figure 3-4); increasing phosphorus loads will undoubtedly lead to a continued trend toward nuisance eutrophication.

In the absence of detailed bathymetric data, lakes were categorized simply as shallow (<5 m maximum depth) or deep (>5 m maximum depth) based on field measurements. In general, shallow lakes had higher nutrient concentrations (mean 0.08 mg L^{-1}; range 0.01-2.6 mgL^{1}, n=38) than deeper lakes (mean 0.03 mg L^{-1}; range 0.007-0.19 mg L^{-1}, n=26). Higher nutrient concentrations were also more common in lakes near to town centers and villages (Figure 3-5). While factors influencing the concentration of people and animals at a given lake include more than simple linear distance, a general trend can be seen in the trophic status and distance from nearest permanent settlement in the data as well as in field observations. All lakes within 20 km of a town were eutrophic to hyper-eutrophic while lakes farther from settlements typically had lower TP values.

Diatoms

Four of the five lakes cored for reconstructions had abundant *Staurosira*, *Staurosirella*, and *Pseudostaurosira* taxa, which were common and abundant throughout regional lakes in the calibration set (Figure 3-6); Takhilt had relatively low abundances of these fragilariod taxa. Takhilt was the most saline of the five cored lakes (Table 3-1) and was unique in having preserved valves of *Anomoeoneis sphaerophora* f. *costata*, and resting spores of the genus *Chaetoceros* in both modern and down-core samples. These taxa were found only in calibration set lakes with high salinity. Takhilt and Baga lakes had the highest proportion of planktonic taxa, the other three lakes had dominantly benthic assemblages. All five lakes hosted *Stephanodiscus minutulus*, which increased in relative abundance at the top of all cores.

Comparisons of modern and fossil species showed that fossil assemblages were well represented in the calibration set. On average 85% (minimum 50%) of species in fossil samples were present in the calibration set. Squared chord distance between each fossil sample and its nearest analogue in the calibration set was within the fifth percentile of the distance distribution within the calibration set (Bennion et al. 2004), indicating minimal floristic differences between fossil samples and their nearest analogue in modern samples.

Productivity over the last 2000 years

Cores from Zagas, Bayan, and Kholboo lakes had sufficiently low sedimentation rates to preserve at least 2000 years of sedimentation in the 1-1.5 m cores. Sediment records recovered from Takhilt and Baga were limited by incomplete core retrieval, relatively high sedimentation rates, and poor diatom preservation in lower intervals. The cores comprise approximately 800 and 650 years of sediment respectively, with diatom counts limited to 600 years before present in Takhilt and to only 100 years in Baga due to poor preservation.

Biogenic silica, sediment phosphorus, and the ratio of planktonic to benthic diatoms (P:B) were used to assess lake productivity over the long records (Figure 3-7). In all lakes except Takhilt, recent increases in these productivity indicators were in excess of normal variability over the past several hundred to several thousand years. Variability in all three productivity indicators was low in the earliest part of the record in Kholboo and Bayan. Kholboo became both more variable and more productive over time, while very few changes occurred in Bayan until the most recent part of the record. Kholboo showed a slight increase in phosphorus at 300-500 AD and an increase in P:B spanning approximately 800-1000 AD. The remainder of the record in Kholboo was fairly stable until biogenic silica and phosphorus fluxes began increasing slowly at approximately 1600 AD, followed by large increases in sediment phosphorus flux, bSi flux and P:B in the last 10-50 years. The record from Bayan showed remarkably stable fluxes of bSi and P, and a total absence of planktonic diatom flora over most of the last 2000 years. A slight increase in bSi and P:B is recorded during the 1800s. Over the last 20 years in Bayan, a rapid rise in sediment phosphorus, biogenic silica and planktonic diatom abundance took place. Zagas had a slightly more variable productivity record with slight increases in all three indicators around 300 AD, 600-1000 AD, and a large peak in silica from1400-1600 AD which was fairly well matched with a small increase in the proportion of planktonic diatoms. In the last few decades in Zagas there has been a rapid increase in P:B and sediment phosphorus along with a continued increase in bSi flux which began around 1850. Takhilt had a highly variable record for all three productivity indicators; however, three periods of increase were coincident for all three parameters, from 1300-1600 AD, 1800-1900 AD and over the most recent two decades. Baga had two peaks in biogenic silica, one around 1700 AD and one beginning in 1990 and continuing to today. Phosphorus flux in Baga was low and stable in the early part of the record with a small increase beginning in 1980 and a very rapid rise beginning in 1990. The diatom record in Baga, available only for the last 100 years, showed very low planktonic diatom abundances until a slow increase over the 1980s followed by a rapid rise after 1990.

Productivity over the last ~120 years

Sediment accumulation rates over the last 120 years varied from approximately 0.01 to 0.05 g $cm^{-2}yr^{-1}$ in the five lakes. Three of the lakes (Zagas, Bayan, and Kholboo) had relatively slow accumulation rates. Zagas had low (0.01 g $cm^{-2}yr^{-1}$) and stable rates throughout the period covered by the core. Both Kholboo and Bayan lakes had similarly low rates of about 0.01 to 0.02 g $cm^{-2}yr^{-1}$ and recorded slight increases in accumulation rates beginning in about 1940. The rate in Bayan increased again in the mid-1990s to a maximum of just over 0.03 g $cm^{-2}yr^{-1}$. Baga had low sediment accumulation rates, similar to Zagas, in the early part of the record, but experienced a rapid increase in the early 1990s reaching rates of over 0.05 g $cm^{-2}yr^{-1}$ in recent years. Takhilt had relatively high (0.03 to 0.04 g $cm^{-2}yr^{-1}$) but steady sediment accumulation throughout the core (Figure 3-8). Lead-210 dating precision was high for the recent record; from the 1940s to the time of coring, dating uncertainty in all cores were between one and two years, except in Zagas where uncertainties were up to four years between 1930 and 2005.

Many of the changes in diatom community composition in the most recent decade were similar among the five lakes (Figure 3-6). All showed marked increases in planktonic species including *Stephanodiscus minutulus*, *Asterionella formosa*, and *Puncticulata radiosa* in the uppermost sections of the core. In Zagas, Baga, Bayan, and Kholboo Lakes planktonic diatoms are virtually absent from the flora until the late 1980s to early 1990s (Figures 3-6 and 3-9). Takhilt Lake had more diverse planktonic assemblages with *Chaetoceros* dominating in the deepest sections, abundant *Cyclotella* species in the intervals from 1920 to 1980 and a switch to abundant *Stephanodiscus minutulus* in the 1990s. Fluctuations in fragilariod speices including *Staurosirella pinnata*, *Pseudostaurosira elliptica*, and a form of *Staurosirella construens* v. *venter* constituted the main up-core changes in Kholboo, Zagas, and Bayan lakes. *Pseudostaurosira elliptica* and *S. pinnata* were found in less nutrient-rich lakes in the calibration set (TP optima=0.02 mg L^{-1} and 0.03 mg L^{-1}, respectively) whereas *S. construens* v. *venter* had a higher nutrient optimum (0.08 mg L^{-1}).

In addition to evaluating species changes individually, the degree of floristic change in the entire diatom assemblage was evaluated for each core using correspondence analysis (CA). Shifts in species scores along a CA axis indicate a change in diatom assemblage. These analyses do not make any connection with causal factors, but simply indicate the degree of change in the assemblages. While the diatom species assemblages in each lake vary in stability over time, all lakes show a shift along the first or second axis in the most recent decade. These shifts, along with marked changes in the ratio of planktonic to benthic species, demonstrate substantial changes in diatom assemblages at the top of the sediment cores (Figures 3-6 and 3-9).

By applying the diatom-based inference model to the five cores, a history of inferred water-column total phosphorus concentration was established for each lake for the past 120 years (Figure 3-9). Because of the variable rates of sediment accumulation, the resolution obtained with centimeter-thick sections varied among lakes. In the three lakes with low and relatively stable sedimentation rates (Kholboo, Zagas, and Bayan), reconstructions were developed at approximately decadal sampling resolution. A common history was apparent in these lakes: diatom-inferred total phosphorus (DI-TP) levels were higher in the most recent sample than at any time in the last century. In Bayan Lake, DI –TP levels were relatively stable from 1875 until a marked increase between 2003 and the top of the core. Zagas Lake recorded slowly increasing phosphorous concentrations since the 1920s with a larger increase between 1990 and 2004. Kholboo Lake had two major periods of high inferred phosphorus, one in the 1920s and 1930s and one in the 1990s.

Two lakes with higher resolution reconstructions had similar but more complex histories. Inferred-TP values in Baga were stable in the early part of the record. Between the mid-1980s and 1990 DI-TP levels increased, then rose further in the mid-1990s. Phosphorus concentration decreased for three years during the *dzud* years of 1999-2003, and increased again to high levels between 2003 and 2005. In Takhilt Lake, DI-TP levels were very high from 1895 to 1915. Diatom assemblages in these intervals were dominated by *Amphora* and *Chaetoceros* species, present only in highly saline lakes in modern samples. In calibration set samples, many saline lakes were high in total phosphorus, potentially owing to the paucity of species that can tolerate elevated salinity and convert available phosphorus to organic matter which can be removed through sedimentation. Additionally, several of these saline lake species have large tolerance ranges for TP and the weighted averaging model for this interval may be more reflective of salinity changes, appearing to have spuriously high total phosphorus. From the 1920s until 1990, DI-TP levels were stable in Takhilt, then increased steadily from the early 1990s to 1999. Similar to Baga, DI-TP levels in Takhilt decreased beginning in 1999, but, in contrast, did not increase again in more recent sediment samples.

In Takhilt and Baga, biogenic silica (bSi) showed changes through time that were synchronous with inferred changes in nutrient load (Figure 3-8). The record in Baga tracked diatom-inferred TP reconstructions, with stable and low bSi flux until the early 1990s, increasing flux until 1995 when flux decreased slightly before increasing after

2003. In Takhilt Nuur, high bSi from 1918 to 1930 followed the period of inferred high TP by several decades. This may indicate accumulation of nutrients during the saline period in the early 1900s followed by a rapid bloom when salinity decreased and a more diverse flora returned to the lake and made use of the accumulated phosphorus. From 1930 to 1993, bSi flux was fairly constant in Takhilt, then increased to its highest level between 1993 and the top of the core. Biogenic silica records in Bayan and Zagas were also similar to inferred TP profiles, with relatively stable flux for most of the record and a small, recent increase. Kholboo had a steadily increasing bSi flux beginning in about 1980 (Fig. 3-8). Due to low sedimentation rates in Zagas and Kholboo, the uppermost sediment section includes nearly 10 years of accumulation, preventing a good assessment of the most recent record of bSi in these lakes. In contrast, additional samples from the sediment-water interface provided higher resolution in the DI-TP reconstructions for the most recent part of the record.

Limited sampling resolution restricted the temporal resolution of sediment phosphorus data in the uppermost intervals of the core. The limited data do show that the flux of phosphorus to the sediments had similar, though not identical, patterns to inferred water-column phosphorus levels. Phosphorus increased markedly in Kholboo, Baga, and Bayan lakes from pre-1990 to post-1990 samples (Figure 3-8), however, the large magnitude of the change to the top sample is likely related to mobility of the phosphorus in the sediment rather than a true measure of changes in flux.

The flux and relative proportion of organic matter (defined as the loss-on-ignition at 550°C) to the sediments was used as an additional measure of in-lake productivity. Carbon to nitrogen ratios (C:N) were used to identify the origin of the organic matter in the sediment; in-lake algal productivity gives a C:N of approximately 12:1 while ratios of about 45:1 are typical of allocthonous organic material (Wetzel 2001). Measured C:N values in the sediments ranged from 3-12 indicating predominantly in-lake productivity (Table 3-1). In Kholboo and Zagas, organic matter fluxes were virtually unchanged over the past 100 years, though the relative proportion of organic matter did increase slightly. Due to low sedimentation rates the top core intervals were dated to only 1996 and 2000 respectively; the sampling resolution may have integrated too much time at the tops of these cores to detect a change if present. Increases in the input of organic matter were apparent in Takhilt in both the early part of the records and again in the most recent decade. Organic inputs in Bayan increased slowly over the last 50 years and then increased again in step with the increase in diatom-inferred water column TP in the early 1990s. Changes in Baga were most pronounced, with fluctuations in organic matter tracking the DI-TP trend in recent years with an increasing flux beginning in about 1980 and rapid increases in organic matter deposition in the early 1990s, followed by a brief decrease in the late 1990s, and an increase corresponding with the most recent rise in DI-TP (Figures 3-8 and 3-9).

Attribution of change and variance partitioning

Most changes in diatom assemblages, sediment characteristics, and DI-TP occurred after the increase in livestock populations in the early 1990s. However, some changes, notably in Baga Lake, began around the time of increasing temperature trends in 1980. The variable resolution of sediment records among the five lakes, as well as the similar timing in climate and land-use changes, made it difficult to attribute changes in lake nutrient concentrations unambiguously to either a warming climate or increased livestock populations based on temporal correlation alone. Partial constrained correspondence analysis (pCCA) using each of four climate variables (composite anomalies in winter temperature, winter precipitation, summer temperature, and summer precipitation) and national livestock population identified trends which were significantly related to changes in diatom assemblages between 1938-2005 (Figure 3-10; Table 3-2).

Changing livestock population and one or more climate variables were significantly explanatory of changes in diatom assemblage in all lakes. Winter temperature was the most significant climate variable in three of the five lakes, with summer temperature the most significant in Bayan Lake and both summer and winter temperature having equal significance in Takhilt Lake (Table 3-2). Not all variables that were significant individually remained significant when the interactive effects with other potential explanatory variables were taken into account.

A CCA for each lake using all individually significant variables enabled interpretation of the importance of each variable in explaining changes in diatom assemblages over time (Figure 3-10). In Baga, Kholboo, and Zagas Lakes, variation in diatom assemblages before the early 1990s was mainly along axis 1, which is most strongly correlated with changes in winter temperature. In all three lakes, the most recent changes tracked along axis 2, which was more strongly correlated with increased livestock numbers. In Bayan Lake, samples from 1999 and 2003 were separated from earlier samples along the gradient correlated with increased animal population; however, the most recent sample was separated from these along a gradient more strongly correlated with increased summer temperature. In Takhilt Lake, many variables had a significant correlation with changes in diatom assemblages. Shifts from the pre-1990 to post-1990 assemblages occurred along a gradient that was correlated with both animal population and winter temperature increases, while the most recent shift was best correlated with summer temperature. Many of these potential explanatory variables are linked to one another, including animal population and climate as seen from the 1999-2003 *dzud* years.

Discussion

Understanding the role of long-term climate, episodic natural disasters, and the impact of humans and domestic animal herds on natural resources is a complex but important objective. Studies conducted in the last 10 years have revealed that Mongolian herders are aware of increasing land degradation, desertification, and reduction in wildlife numbers and that changes in grazing practices are affecting the grazing lands (Bedunah and Schmidt 2004). While the inherent value of aquatic biodiversity is often harder to recognize than that of larger mammals or grasses for grazing, the effects of eutrophication on the overall health of the ecosystem and access to clean water can be profound. A 2004 report from the United Nations Development Program found that between 1995 and 2003, 683 stretches of river and 760 lakes and ponds in Mongolia had disappeared due to a combination of climate and land use changes. Additionally, the number of improved wells in the country had decreased by more than 2000 since 1990 (Batbold et al. 2004). With a community so dependent on natural surface waters for both human consumption and livestock management, maintaining water quality is of critical importance. As research on the effects of land use and best management practices for grazing continues (e.g. Fernández-Giménez 2002) consideration of the combined impact of climate change and heavy grazing on aquatic ecosystems will play an important role in conservation efforts.

Our study of 65 lakes in western Mongolia was a first step in evaluating the modern water quality from the region. The development of sediment core records from five lakes in the region allowed for the reconstruction of detailed records of water quality change over the past 120 years and a lower resolution comparison of productivity records over the past 600-2000 years, which allowed us to begin making connections between climate, grazing practices, and water quality. Results showed that climate warming and increased concentration of grazing in small areas are likely combining to cause detrimental impacts to the water quality of lakes in this region.

Analysis of multiple indicators of historical lake conditions showed an overall pattern in all cores indicating increasing nutrient concentrations, productivity, and eutrophication in the early to mid-1990s. Diatom-inferred total phosphorus levels in Kholboo, Bayan, and Zagas Lakes increased to their highest levels between the early 1990s and today in conjunction with a shift to more planktonic diatoms, which are indicative of more eutrophic conditions, increased diatom abundance (as inferred from bSi), and increased flux of organic matter in Bayan Lake. Two lakes nearer to permanent settlements, Takhilt and Baga, had higher sedimentation rates than the other lakes; consequently trends in inferred water-column phosphorus could be reviewed with greater detail. In both lakes DI-TP increased from approximately 1990 to 1999, decreasing markedly during the recent *dzud* years (1999-2003), and in Baga increasing again with the recent rebound in herd sizes after 2003. In these two lakes increased diatom abundance and flux of autochthonous organic matter also support a recent and rapid rise in nutrient concentrations. Baga Lake, however, also records a more gradual shift concurrent with increasing temperatures beginning in about 1980. Variance partitioning indicated significant relationships with both grazing and climate in all five lakes. Our results therefore suggest that recent and synchronous changes in water quality are taking place across western Mongolia, and can be best linked to a combined effect of increased herd sizes with increased grazing intensity, especially near population centers, and warming temperatures.

Increased warming is expected to increase phosphorus concentrations in many phosphorus-limited lakes due to a combination of changes in wind mixing and stratification, biotic uptake of phosphorus, and other factors (Malmaeus et al. 2006; Niemestö and Horppila 2007). Observations in the U.S. Great Lakes have also shown that decreased ice cover in warm winters can lead to increased water column phosphorus due to decreased sedimentation and increased re-suspension in windier ice-free conditions (Nicholls 1998). Recent climate change has strongly affected Mongolia, most notably with warmer winter temperatures (Batima 2006; KNMI 2007), and reduced ice cover has been reported (Batima 2006). The two decades of steady warming may explain some of the small shifts in species composition and inferred TP prior to the 1991 market transition. However, the temperature shift has been gradual and no major fluctuation occurred in the early 1990s when most lakes showed the most pronounced shift in diatom communities and sediment properties. Additionally, the rapid swings in sediment composition and DI-TP in the two more ‘urban’ lakes (Baga and Takhilt) are coincident with the rapid shifts in herd size during the *dzud* years. While *dzud* is a short-term climate anomaly, it is linked mainly with precipitation and not with temperature. Neither summer nor winter temperatures had a persistent deviation from the mean during the years 1999-2003. These observations point to changes in human and animal impact on the landscape, rather than climate change, as the main driver for recent eutrophication.

Links between grazing and increased nutrient input to the lakes are apparent today, however, the increase in herd size in the 1920s and 1930s was not clearly reflected in changes in nutrient concentration, except in Kholboo lake. The removal of Chinese government controls in 1911 decreased food security and led to many of the same free market demands as are seen in the recent transition; however, the development and growth of many small cities during the Soviet socialist era may have created a different dynamic wherein many more people were removed from traditional herding practice for a much longer time, allowing for a greater loss of traditional systems prior to the free market period. Additionally, the two lakes showing the greatest changes and strongest link to herd size fluctuations were near town centers; Takhilt was less than 10 km from Nömrög, a village in the Zavkahn *aimag* (province), and Baga was only 2 km from Züüngov in Uvs *aimag*. Such town centers were less populous or non-existent in the early 1900s. Now focal points for herders with few resources, these areas will likely experience the greatest impact from overgrazing.

Not all changes in diatom-inferred TP exceeded the error of the inference model; inferred shifts exceeding the model errors were limited to the largest changes in Baga and Takhilt lakes. Errors for phosphorus models are notoriously high (Sayer 2001); however, other models with RMSEP in the same range as the model used here have been shown to reliably infer TP when compared with instrumental records (Bradshaw and Anderson 2001). Total phosphorus is a secondary gradient in the calibration set lakes, with slightly less influence on diatom distributions than lake salinity. Because many species are more sensitive to one gradient than the other and both gradients show significant independent effects (Shinneman et al. in press) the upcore species shifts to taxa that thrive under high nutrient conditions (Figures 3-6 and 3-9) are interpreted as real shifts in nutrient concentration, not artifacts of shifts in the primary salinity gradient. Fragilarioid taxa such as *Staurosirella* and *Pseudostaurosira* often have wide tolerances for nutrients and changes in their abundance may reflect habitat variability rather than changes in nutrient availability (Bennion et al. 2001). While these taxa may be responding to changes in nutrient concentrations in the lake, shifts in their abundance are considered a less robust indicator of change than the marked increase in plankton. Despite the potential for confounding effects in the model, common trends among the five cores indicate a high degree of temporal coherence in water quality changes over the last century. These cores spanned the geographic range of the study area as well as a large gradient in elevation and included lakes of varying size and depth. The consistent patterns throughout these widely spaced and unique systems indicate that recent eutrophication is likely widespread. Impacts near town centers were more concentrated and changes more rapid than in lakes farther from permanently settled sites.

Caution must be exercised in interpretation of changes in the uppermost intervals of a core, acknowledging the possibility of diagenetic effects on the sediment. The mobility of silica and phosphorus near the sediment water interface and the mineralization of organic matter with burial are important considerations in the interpretation of recent sediment records; studies have shown that the concentration of mobile elements in a given sediment interval decreases over time thorough diagenetic processes (Gälmen et al. 2008). The top several centimeters of a core may therefore have higher concentrations of a given element compared with more compacted and deeply buried sediments without any changes in input to the lake. This possibility makes the large increases in sediment phosphorus at the tops of some cores suspect; however, while the large magnitude of the increases in lakes like Bayan and Baga are potentially artifacts of the core top, the trends, which align with other, more stable, proxies are likely real. Many of the other proxies agree in timing with one another and with diatom records, additionally major changes such as the organic matter increase in Bayan, Baga, and Takhilt occur at the same date, but at different depths in the sediment indicating the changes are more likely related to a synchronous regional change than to depth-related diagenesis. As diatom samples were counted, a tally was kept of the number of valves with significant visible dissolution. In the last 100 years, significant dissolution (> 5% of valves) was encountered only in the short inferred-saline interval in Takhilt lake from 1900-1920 and there was no evidence of preferential dissolution as has been encountered in other saline lake regions (e.g. Ryves et al. 2006). The representation of diatom species and P:B ratios should therefore not be expected to change after burial. In the longer core records, diatom dissolution occurred in two lakes; significantly dissolved valves appeared abruptly at 100 cm depth in Takhilt Lake, and 130 cm depth in Baga lake. Intervals below these depths were not counted, however little to no dissolution was observed above these intervals.

Most proxy records of productivity showed a recent increase that was equal to or greater than the largest increases in the 2000 year records. Earlier periods of high productivity occurred during times recorded as warm intervals in regional tree ring records (D'Arrigo et al. 2001; Figure 3-7). While increases in productivity with recent warming might be expected to be analogous with productivity increases during previous warm intervals, the rapid increases in planktonic diatoms in all lakes along with unprecedented increases in several other productivity proxies indicated that recent changes are in excess of past warm period increases in productivity. This underscores both the magnitude of recent changes, and the likelihood that in addition to warming, a new driver, such as land-use, must be contributing to the recent changes.

Variance partitioning indicated that not all of the variables which may drive changes in diatom communities had significant unique explanatory power; however, some combination of changes in climate and animal population was significantly explanatory for changes in all five lakes. This outcome points to both the combined effect of climate and land use on the trophic state of the lakes and the need for further study to refine, and remedy, the driving factors behind recent changes.

Conclusions

With this study we provide evidence that the effects of increased grazing intensity and regional climate change are reaching beyond the grasslands and affecting the health of aquatic ecosystems throughout western Mongolia. Diatom assemblages are markedly different in pre-1990 and post-1990 sediments, indicating a major biotic shift in the lake ecosystem. Sediment records indicate that the heavily impacted conditions observed today do not represent the status quo for Mongolia, but are recent and temporally linked to market-driven changes in grazing intensity and a warming climate.

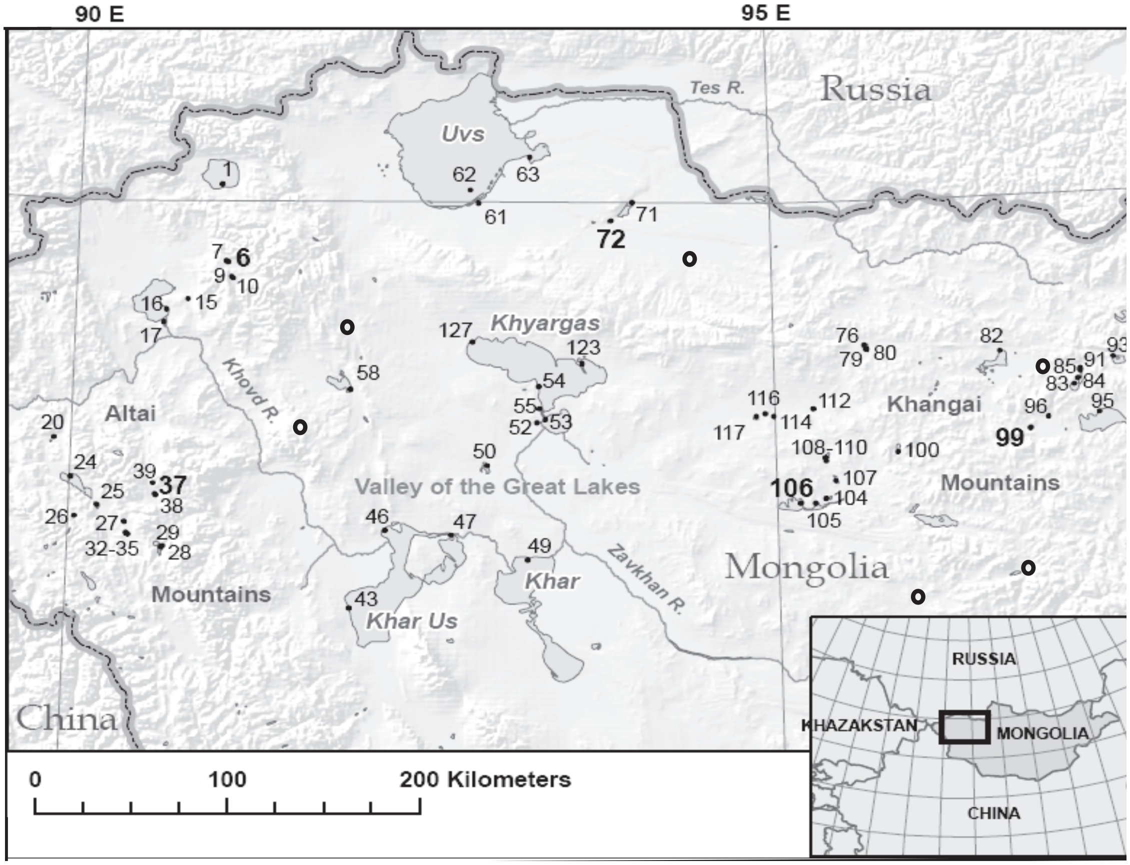


Figure 3-1: Western Mongolia and study area detail. Sites with sediment core reconstructions are labeled in bold numbers: Kholboo (6), Zagas (37), Baga (72), Takhilt (99), Dune Bayan (106) (see Table 3-1). Weather station locations are indicated with an open circle.

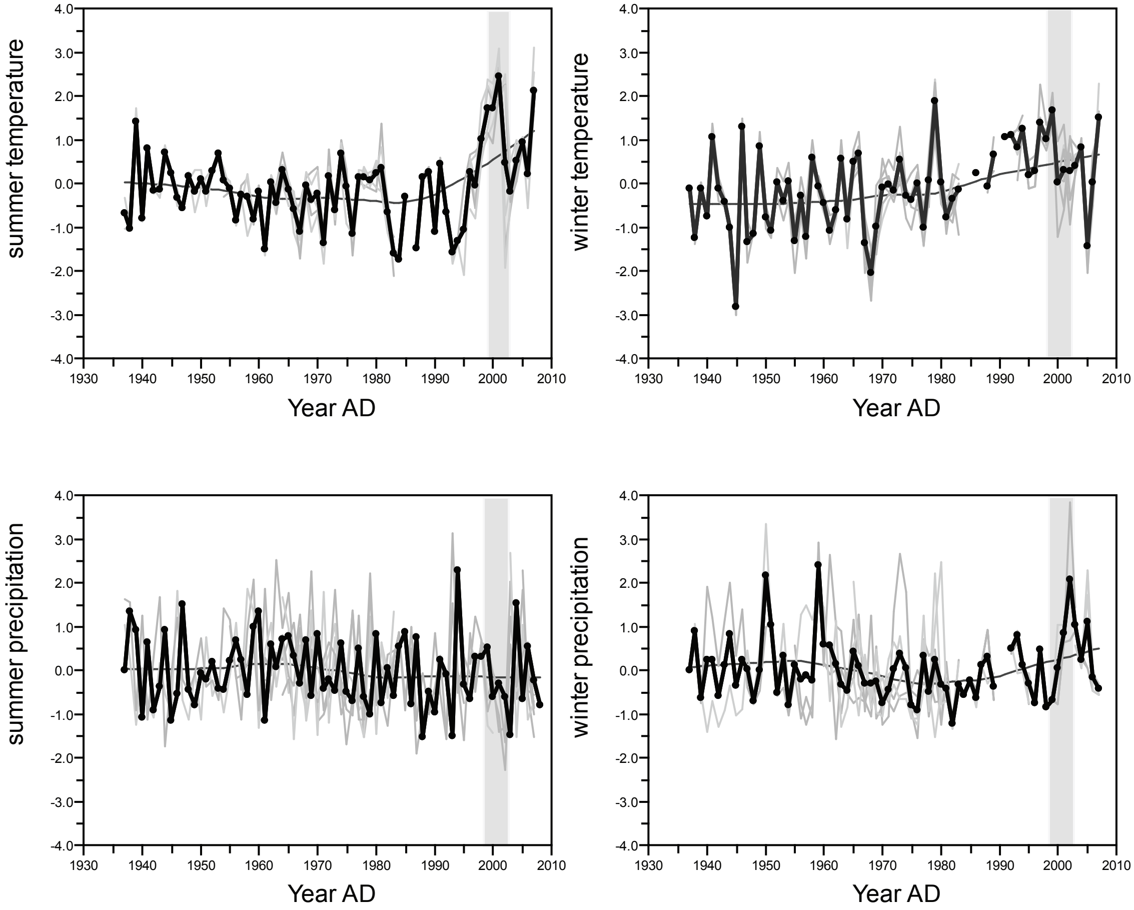


Figure 3-2: Weather station records from the Global Historical Climate Network (GHCN) (KNMI, 2007). The composite records (the average anomaly from six stations) is shown as a dark line with points for each sample, each station record individually is shown as a lighter grey line. Regional temperature anomalies are similar across all six stations, while precipitation is more variable from site to site. Recent dzud years (shaded) are clear in the precipitation records with summer drought followed by heavy snowfall. The solid horizontal line is a LOWESS smooth (span=0.45).

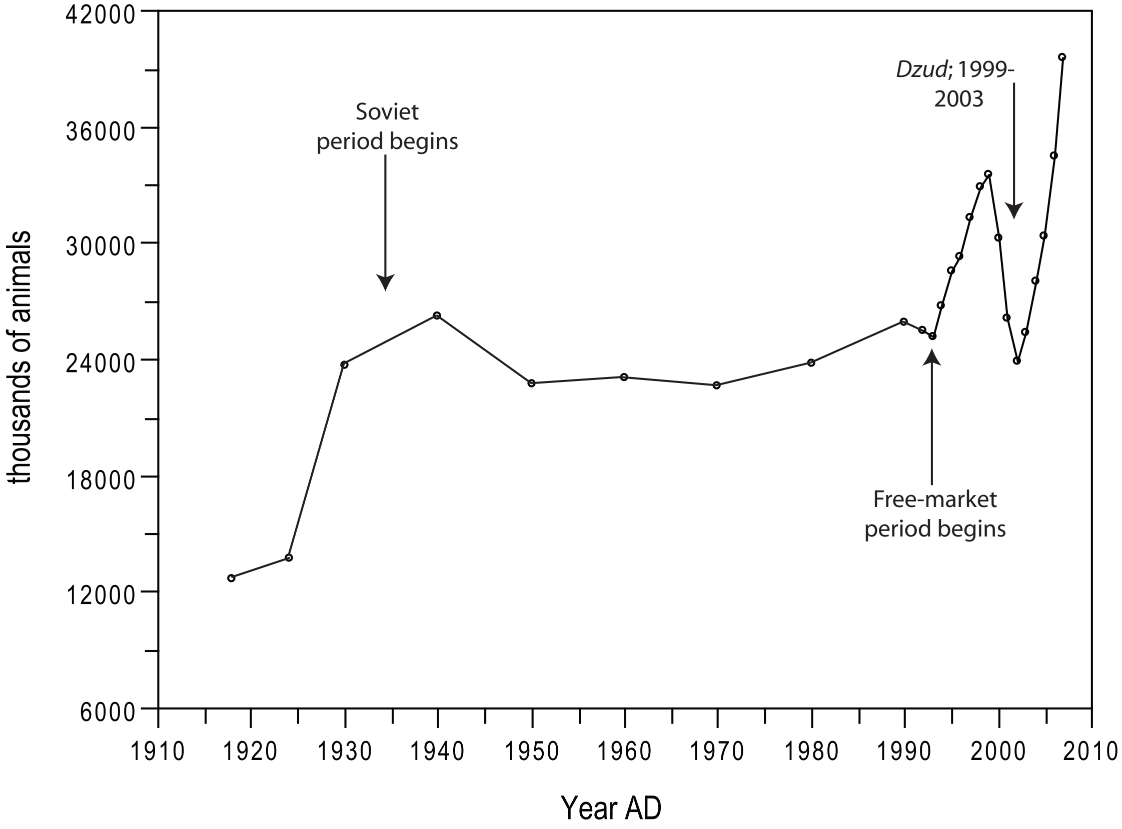


Figure 3-3: The total number of grazing animals in Mongolia in thousands of animals, 1918-2007. National herd size increased markedly at the beginning of the Soviet era in the 1930s and again following the transition to a free market economy in 1991. The dzud of 1999-2003 resulted in the loss of millions of animals, but numbers have increased again in recent years. Data for 1918-1990 (Bold, 1998); 1990-1998 (World Bank, 2003); 1999-2005 (FAO, 2007), 2006-2007 (Ulaan Baatar Post, 2007).

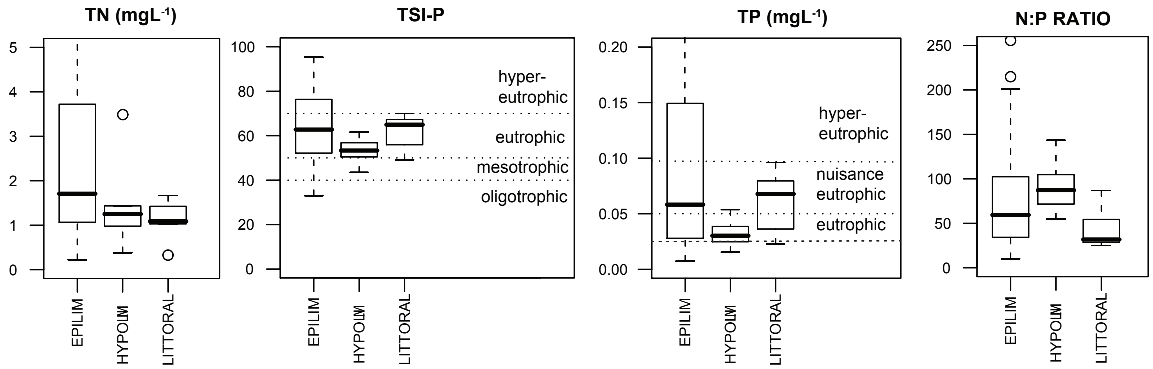


Figure 3-4: Summary of nutrient measurements (total nitrogen-TN, trophic status index-TSI, total phosphorus –TP, and N:P ratio) for 65 lakes (Table 1-1). Center line marks median value, box encloses 25th and 75th percentiles, range is marked with dashed line and outliers included as open circles. Epilimnetic samples were taken from all lakes (n=65), hypolimnetic samples were taken from stratified lakes (n=5) and littoral samples were taken when emergent vegetation was prevalent (n=6) Categories based on U.S. Environmental Protection Agency standards (EPA 2000).

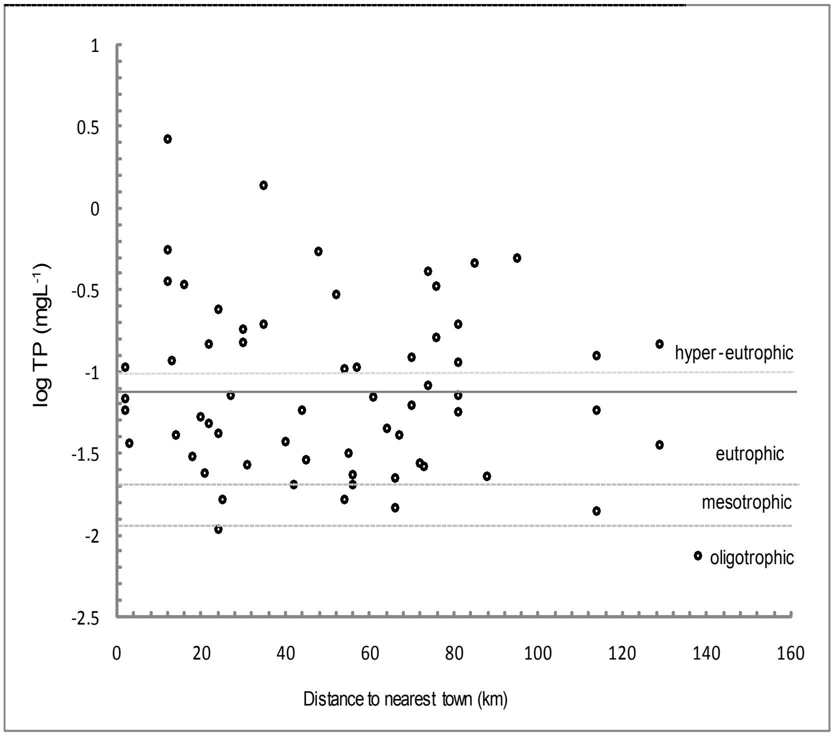


Figure 3-5: Total phosphorus (TP) as a function of distance to permanent settlements. While there is only a weak correlation, especially in the middle distances, it is clear that the most eutrophic systems are near town centers, every lake within 20 km of a town is eutrophic, while the few mesotrophic to oligotrophic systems are farther away. The solid line denotes the average TP value for the data set, dashed lines are trophic state categories (EPA 2000).

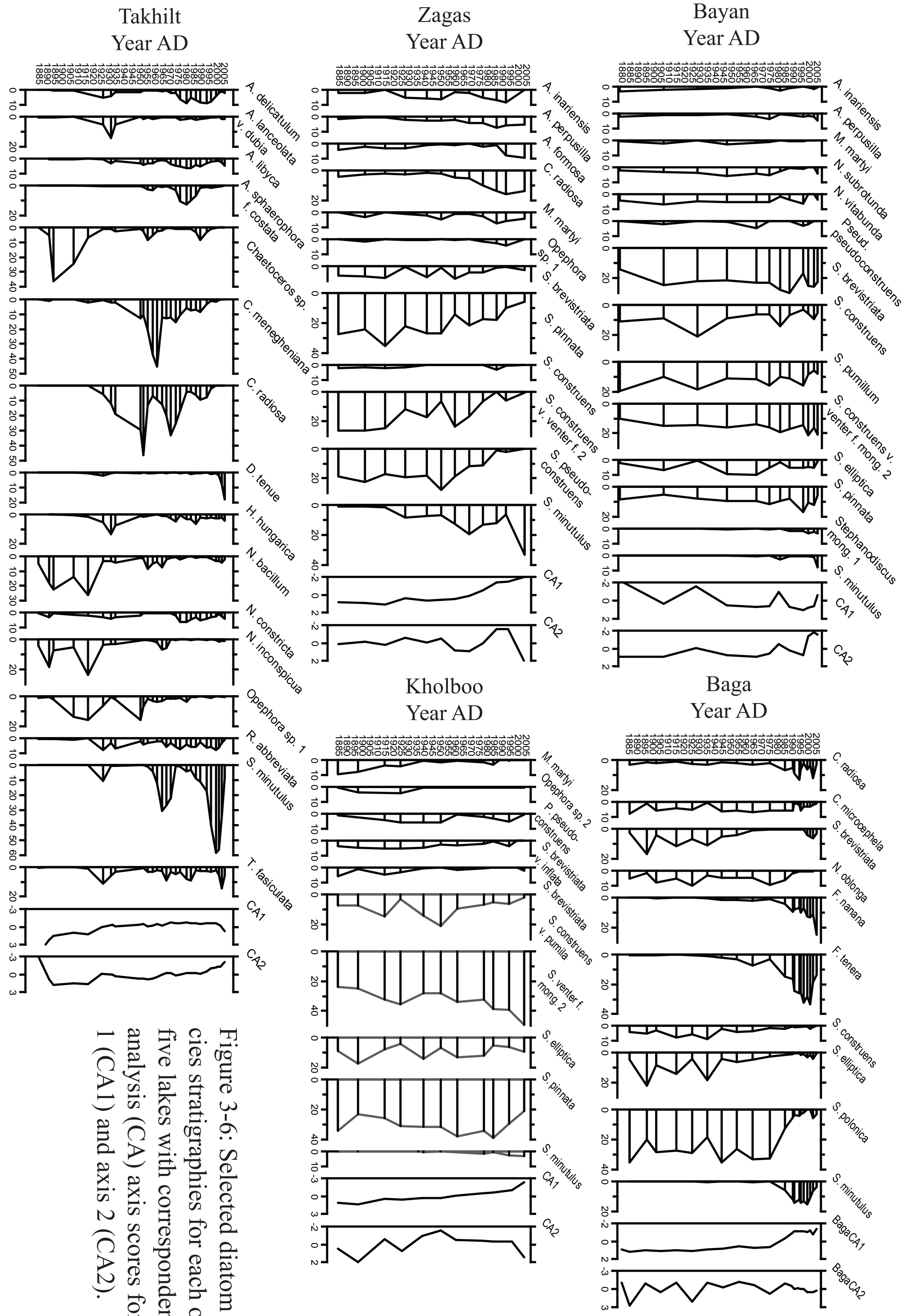


Figure 3-6: Selected diatom species stratigraphies for each of the five lakes with correspondence analysis (CA) axis scores for axis 1 (CA1) and axis 2 (CA2).

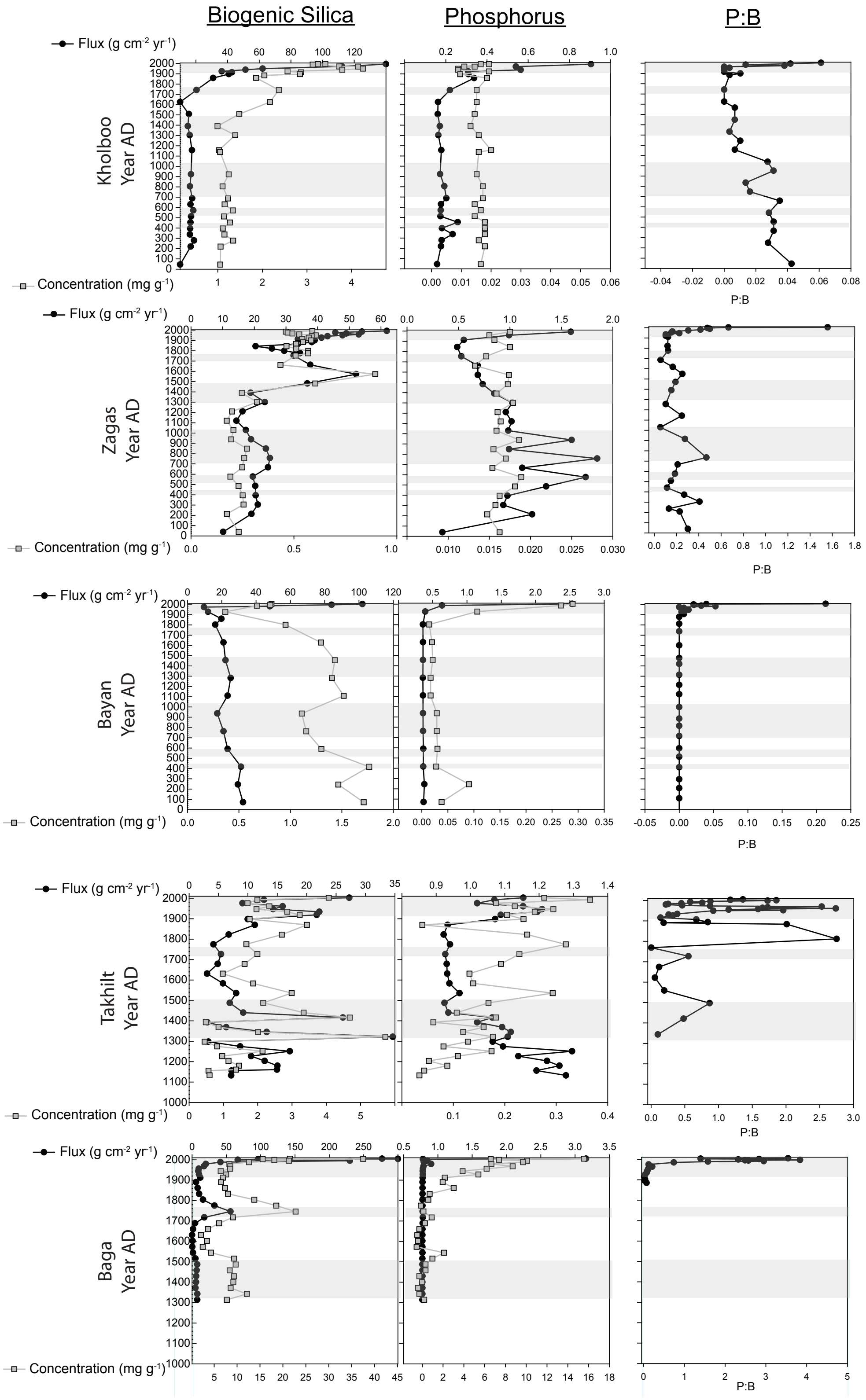
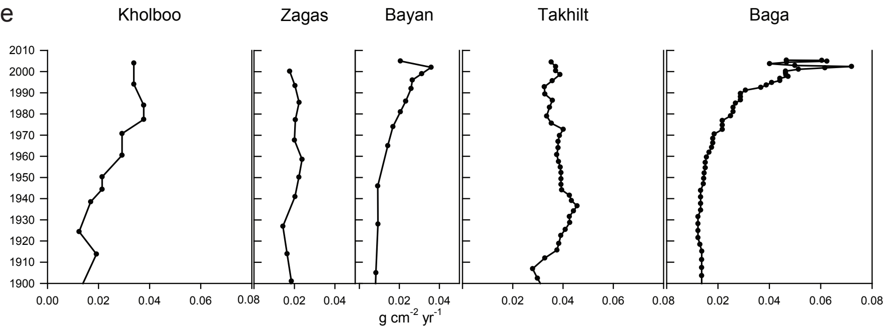
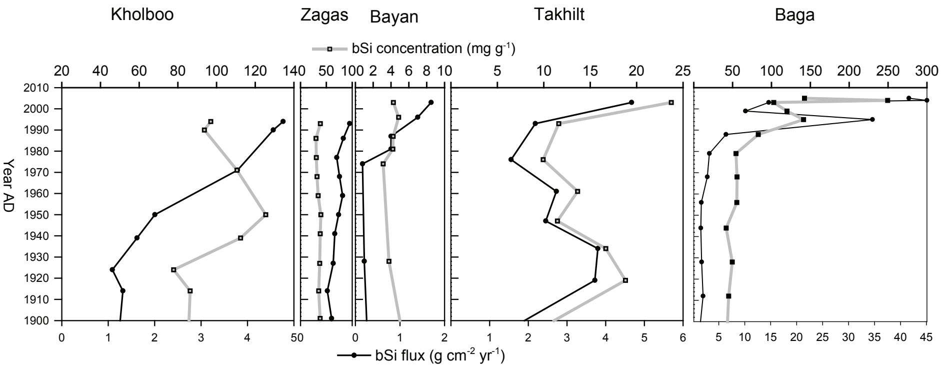


Figure 3-7: Biogenic silica flux, sediment phosphorus flux, and diatom P:B for up to 2000 years in the five cores. Warm intervals identified in regional tree ring records (D'Arrigo et al. 2001) are shaded.

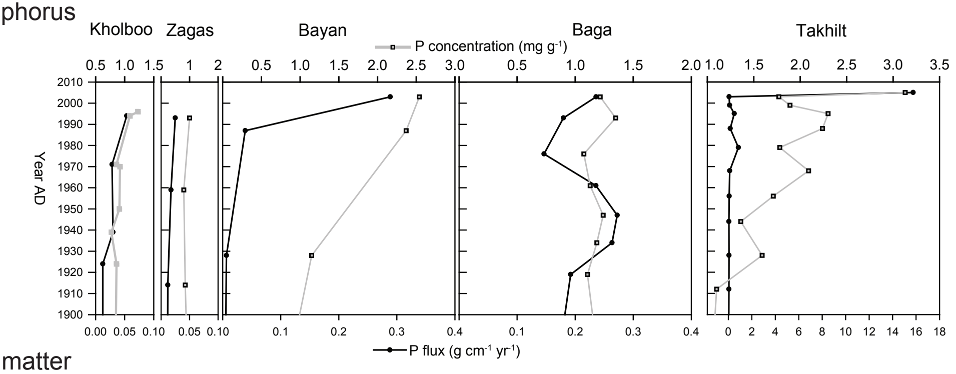
(a) Sed. rate



(b) bSi



(c) Phosphorus



(d) Org. matter

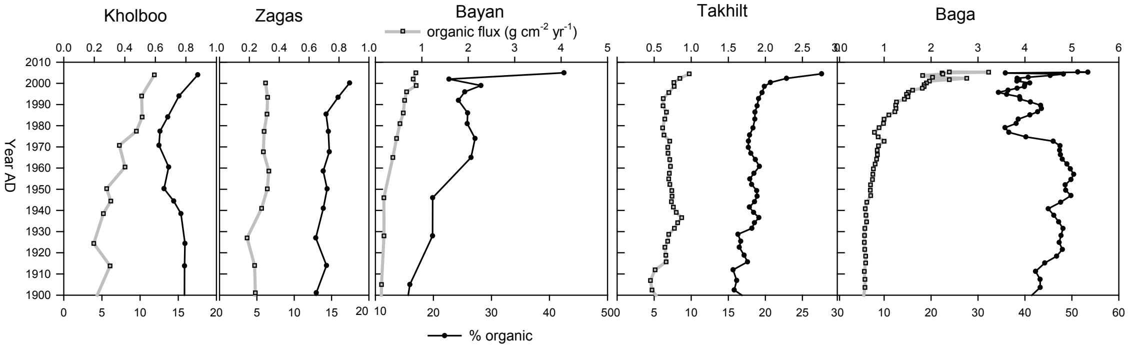
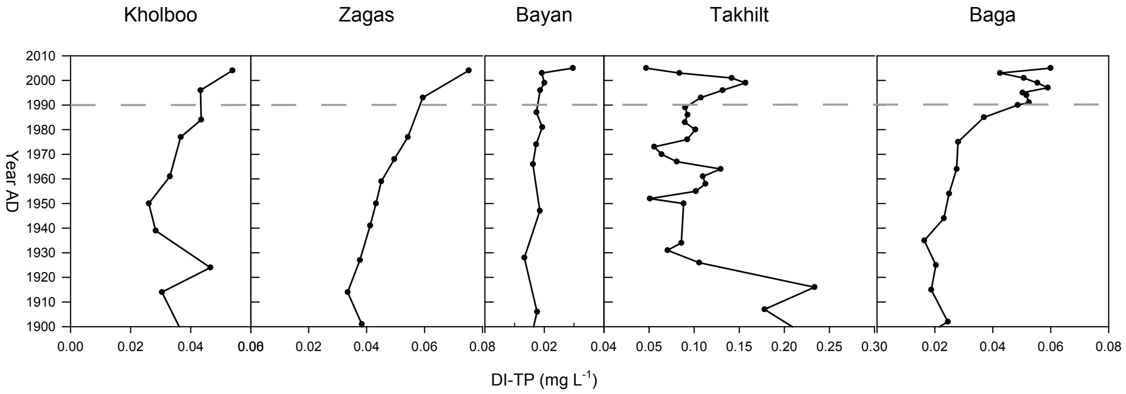


Figure 3-8: Total sedimentation rate (a), biogenic silica flux and concentration (b) sediment phosphorus flux and concentration (c), and flux and percentage of organic matter for the cores (d). Sampling resolution and top date varies with sedimentation rate. Figures are scaled by the bottom axis, top axis scale varies; bSi and P for Baga is not to scale.

(a) Diatom-inferred total phosphorus



(b) P:B

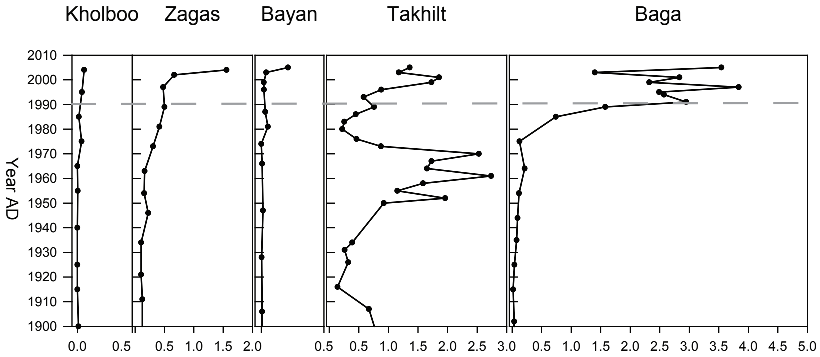


Figure 3-9: (a) Diatom inferred TP; Takhilt and Baga are not to the same scale and (b) planktonic to bethic ratio (P:B). Dashed line is at 1991.

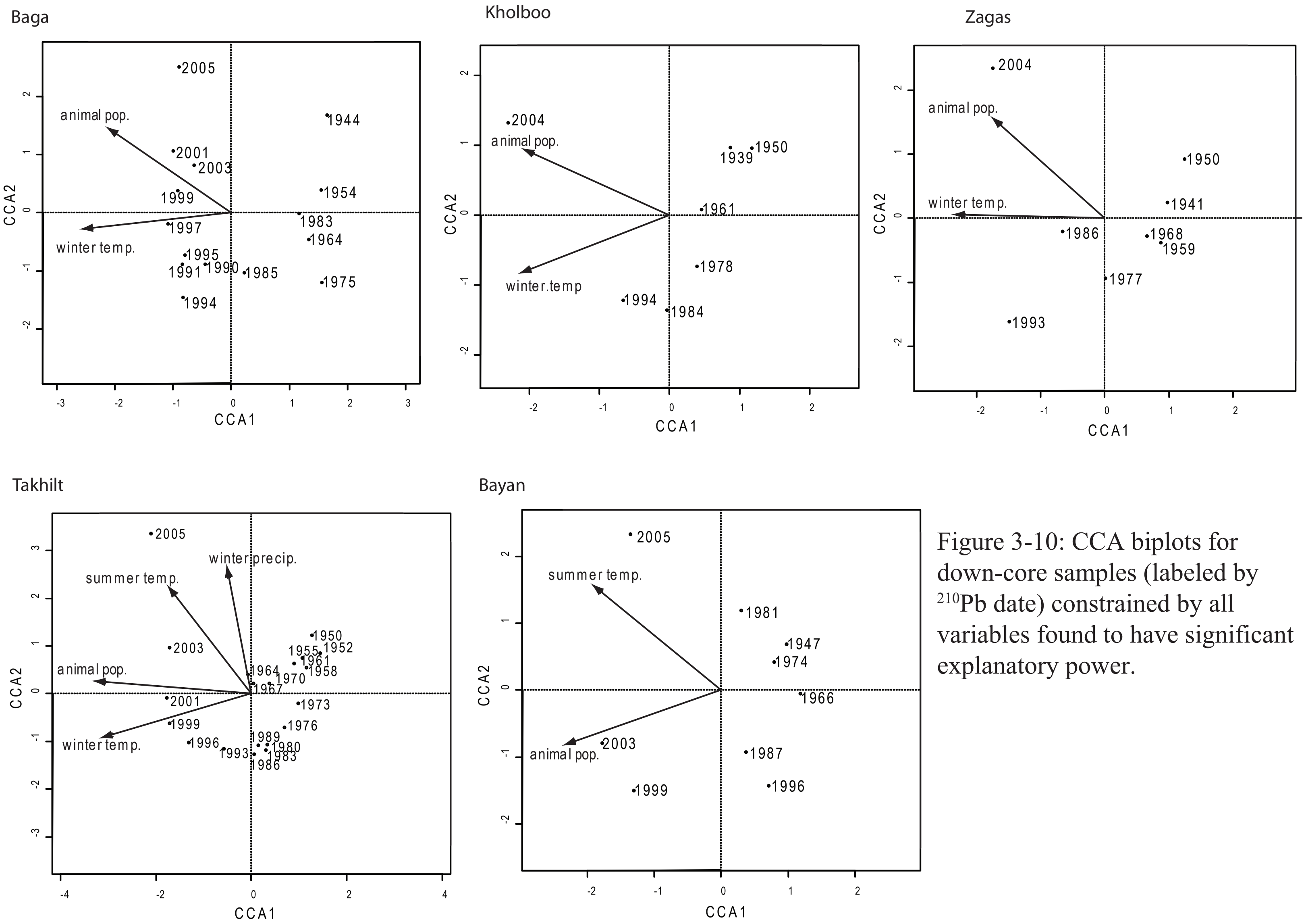


Figure 3-10: CCA biplots for down-core samples (labeled by ^{210}Pb date) constrained by all variables found to have significant explanatory power.

SITE NUMBER	SITE CODE	SUB-SITE	SITE LAT (N)	SITE LONG (E)	ELEV (m)	TP (mg L^{-1})	TN (mg L^{-1})	N:P	SC (µS cm^{-1})	C:N
Freshwater Lakes										
71	BAYANR	EPI	50.0	94.0	981	0.007	0.499	67.3	465	6.54
106	DBAYAN	EPI	48.5	95.2	1481	0.011	0.410	37.8	370	6.94
	DBAYAN	HYPO	48.5	95.2	1481	0.015	0.380	24.8	413	
10	BUYANT	EPI	49.6	91.1	2553	0.014	0.869	62.1	319	10.75
	BUYANT	HYPO	49.6	91.1	2553	0.039	1.251	32.4	437	
26	ALKHAR	EPI	48.4	90.0	2510	0.015	0.319	21.9	41	10.61
24	TOLBON	EPI	48.6	90.0	2079	0.020	0.938	46.3	951	6.45
47	DALAIN	EPI	48.3	92.7	1156	0.022	0.601	26.9	161	12.04
	DALAIN	LIT	48.3	92.7	1156	0.096	1.089	11.3	199	
46	KHRUSN	EPI	48.3	92.2	1157	0.023	0.262	11.4	120	9.07
	KHRUSN	LIT	48.3	92.2	1157	0.023	0.326	14.4	147	
16	ACHITN	EPI	49.5	90.7	1438	0.026	1.709	65.4	328	7.93
49	KHARNR	EPI	48.2	93.2	1132	0.027	1.318	48.2	262	7.08
105	KHUNT2	EPI	48.5	95.3	1505	0.030	1.069	35.7	250	6.51
7	OLONN2	EPI	49.7	91.1	2568	0.035	0.544	15.4	78	10.18
	OLONN2	LIT	49.7	91.1	2568	0.080	1.030	12.9		
96	YALAAT	EPI	48.9	96.9	1824	0.036	0.887	24.5	220	
17	ZUUNKH	EPI	49.4	90.6	1437	0.040	1.621	40.2	383	7.96
85	KHUNTN	EPI	49.0	97.2	1939	0.042	2.893	69.0	2958	11.42
39	KHAGNR	EPI	48.6	90.6	2426	0.045	1.509	33.5	282	8.64
20	SHARNR	EPI	48.8	89.9	1995	0.048	1.941	40.8	2380	9.62
83	KHOLB2	EPI	49.0	97.1	1940	0.052	2.689	51.5	2772	11.71
32	XOXNR1	EPI	48.3	90.4	2232	0.056	0.607	10.8	2200	
107	KHOLB3	EPI	48.6	95.4	1560	0.058	1.139	19.7	296	7.52
9	BARSAL	EPI	49.6	91.1	2530	0.058	2.872	49.3	357	
37	ZAGASN	EPI	48.5	90.6	2376	0.062	0.931	15.1	473	9.73
72	DNBAGA	EPI	49.9	93.8	981	0.068	1.755	25.9	977	9.68
	DNBAGA	LIT	49.9	93.8	981	0.036	1.425	39.3	938	
25	JJTOLB	EPI	48.4	90.2	2089	0.069	1.063	15.4	216	8.46
35	XOXNR4	EPI	48.3	90.4	2223	0.071	1.043	14.7	1530	
43	KHRUSS	EPI	47.9	92.0	1157	0.071	1.928	27.1	197	9.76
	KHRUSS	LIT	47.9	92.0	1157	0.068	1.668	24.6	215	
33	XOXNR2	EPI	48.3	90.4	2228	0.113	1.480	13.1	3000	
38	ARALNR	EPI	48.5	90.6	2375	0.122	1.529	12.5	489	11.94
27	ALALTN	EPI	48.4	90.4	2211	0.123	0.983	8.0	225	

Table 3-1: Location and select water chemistry data for regional lakes. Site numbers are as in Figure 3-3. Saline lakes are those with SC>3000 µS cm^{-1}.

SITE NUMBER	SITE CODE	SUB-SITE	SITE LAT (N)	SITE LONG (E)	ELEV (m)	TP (mg L^{-1})	TN (mg L^{-1})	N:P	SC (µS cm^{-1})	C:N
6	KHOLBO	EPI	49.7	91.1	2570	0.145	1.515	10.5	69	9.58
91	TSETNR	EPI	49.1	97.2	1933	0.151	3.250	21.6	771	10.57
84	ULAANR	EPI	49.1	97.2	1935	0.180	4.647	25.8	1990	9.64
52	ZOSTNR	EPI	48.9	93.3	1032	0.340	4.103	12.1	404	7.39
79	TSVPD2	EPI	49.2	95.7	1622	0.492	3.755	7.6	1740	
78	TSVPD1	EPI	49.3	95.6	1635	0.763	1.848	2.4	1040	
Saline Lakes										
62	UVSNRS	EPI	50.1	92.8	759	0.016	1.155	70.1	20682	11.07
95	TELMEN	EPI	48.9	97.3	1789	0.017	1.505	91.0	8630	8.24
123	KHYAR2	EPI	49.2	93.6	1028	0.020	0.962	47.8	9450	11.66
63	UVSNRE	EPI	50.3	93.3	759	0.023	1.173	51.2	20363	7.85
53	AIRIGN	EPI	48.9	93.4	1030	0.024	1.091	46.3	4350	7.82
	AIRIGN	HYPO	48.9	93.4	1030	0.030	1.435	47.4	600	
54	KHYARG	EPI	49.1	93.3	1028	0.027	1.084	39.6	8610	7.58
	KHYARG	HYPO	49.1	93.3	1028	0.025	0.979	39.5	8710	
93	BELTLK	EPI	49.2	97.4	2040	0.028	2.770	97.2	3252	8.03
	BELTLK	HYPO	49.2	97.4	2040	0.054	3.486	64.9	3625	
127	KHYAR3	EPI	49.3	92.8	1028	0.031	1.147	36.7	9400	9.07
112	TSAGN1	EPI	48.9	95.3	1458	0.037	4.268	115.6	29083	13.51
99	TAKILT	EPI	48.8	96.8	1841	0.041	2.085	51.3	3370	8.36
82	OIGONR	EPI	49.2	96.6	1680	0.058	4.849	84.1	32276	9.08
80	TSVPD3	EPI	49.2	95.7	1650	0.082	3.137	38.3	15325	7.83
117	TSAGN2	EPI	48.9	94.9	1370	0.104	2.780	26.9	12830	11.22
61	UVBAGA	EPI	50.0	92.9	759	0.105	2.726	26.1	26391	8.93
58	KHRUS2	EPI	49.1	92.0	1567	0.106	1.677	15.9	5425	9.13
1	UUREGN	EPI	50.1	91.0	1425	0.111	0.242	2.2	6100	
104	GASHUN	EPI	48.5	95.3	1520	0.115	3.809	33.0	3300	7.97
55	SHUVUU	EPI	49.0	93.3	1019	0.148	2.838	19.2	10300	
29	DOROON	EPI	48.2	90.7	2394	0.159	2.626	16.5	4543	19.73
34	XOXNR3	EPI	48.3	90.4	2225	0.194	4.357	22.5	7900	
100	TSEGEN	EPI	48.7	95.9	1882	0.196	3.688	18.9	12430	10.99
50	SNGDAL	EPI	48.7	93.0	1040	0.239	7.184	30.1	178300	9.98
116	OLGOIN	EPI	48.9	94.9	1382	0.296	4.581	15.5	8550	11.85
28	JJDORO	EPI	48.2	90.7	2394	0.328	4.624	14.1	7500	8.69
110	DEVPD2	EPI	48.7	95.4	1540	0.354	6.253	17.6	200000	
76	TSAVDN	EPI	49.3	95.6	1620	0.408	8.224	20.2	173400	
15	BAGANR	EPI	49.5	90.8	1547	0.461	5.827	12.6	7050	10.39
114	PNKTAK	EPI	48.9	95.0	1369	0.535	8.302	15.5	191500	17.19
108	DEVTER	EPI	48.7	95.3	1540	0.557	9.639	17.3	190000	11.91
102	TSGNPL	EPI	48.7	95.9	1882	1.363	12.435	9.1	25500	
109	DEVPD1	EPI	48.7	95.3	1540	2.635	12.114	4.6	42900	

Table 3-1 continued

		% variance explained	significance
Kholboo			
animal pop.			
	total	33%	p≤0.05
	unique	19%	p≤0.1
winter temp.			
	total	34%	p≤0.01
	unique	20%	p≤0.1
Baga			
animal pop.			
	total	28%	p≤0.005
	unique	6%	----
winter temp.			
	total	38%	p≤0.005
	unique	16%	p≤0.01
Zagas			
animal pop.			
	total	24%	p≤0.1
	unique	10%	----
winter temp.			
	total	35%	p≤0.005
	unique	21%	p≤0.1

		% variance explained	significance
Takkilt			
animal pop.			
	total	22%	p≤0.005
	unique	5%	p≤0.1
winter temp.			
	total	21%	p≤0.005
	unique	5%	----
summer temp.			
	total	13%	p≤0.005
	unique	6%	p≤0.1
winter precip.			
	total	10%	p≤0.05
	unique	7%	p≤0.05
Bayan			
animal pop.			
	total	22%	p≤0.01
	unique	17%	----
summer temp.			
	total	19%	p≤0.1
	unique	14%	----

Table 3-2: Total variance in diatom communities explained (without including overlapping or interactive effects of other individually significant variables) and unique variance explained (variance which remains when other significant variables are used as conditional co-variables), and significance for all individually significant explanatory variables in each lake.

Chapter 4

Late Holocene moisture balance inferred from lake sediment records in western Mongolia

Abstract

The Valley of the Great Lakes in western Mongolia is a unique ecosystem comprising a wide variety of terrestrial and aquatic habitats. Relatively little is known about the long-term climate history of the area or the relative impact of changes in climate and land-use in the region. Rising temperatures in Mongolia have made an improved understanding of the regional climate a pressing concern. Tree-ring records for the past several hundred to two thousand years have established an understanding of regional temperature fluctuations; however, the few records of moisture balance from Mongolia offer little insight into potential changes in the precipitation-to-evaporation balance in the region with warming temperatures. Modern and paleo-climatic records from across arid Central Asia show substantial temporal and spatial variability in the correlation between temperature and moisture availability and climate models are inconsistent in predictions for future changes with continued warming.

In order to help refine the understanding of moisture balance in the region, we have developed a 2000-year diatom-inferred record reconstructing changes in lake salinity from western Mongolia that demonstrates a negative correlation between temperature and effective moisture (warm-dry and cool-wet conditions) over this time period. There is higher correlation between diatom-inferred salinity and tree-ring inferred growing season temperature in the past than in the modern record. Modern temperature increases are occurring predominantly in the winter, which may indicate seasonal differences in warming between past warm periods and modern warming.

Whereas some nearby areas, particularly the Tibetan plateau, are notable for climate records free from strong anthropogenic influence, Mongolian grasslands have seen substantial human impacts over the last several decades. Records from the last approximately twenty years show evidence of eutrophication and must be interpreted carefully to understand the individual and combined impacts of climate and land use on sedimentary records and the potential of human-environment interactions to confound inferences about climate changes.

Introduction

In arid Central Asia, water resources are important for ecological, social, and economic viability. In Mongolia, the traditional pastoral economy depends on limited freshwater resources and contributes substantially to the national economy as well as to individual subsistence. Recent *dzud* events, a regional natural disaster characterized by summer drought followed by severely cold and/or snowy winters, have contributed to the deaths of millions of livestock and have increased concern over the impact of continued warming on moisture availability and changing weather patterns in Mongolia (e.g. Siurua and Swift 2002; Shinoda and Morinaga 2005). Mongolia is also home to several unique and endangered habitats (Olson and Dinerstein 1998) and is an important stopover point for migratory birds (Brinson and Malvárez 2002), which depend on lake and wetland ecosystems. Salinization due to increased evaporative losses may threaten the biodiversity and ecosystem health of both freshwater and saline systems (Williams 2002).

Over the course of the approximately 60 years of instrumental weather station data in the area, mean annual and summer precipitation values have been highly variable, with no significant positive or negative trend (Batima and Dagvadorj 2000; Nandintsetseg et al. 2007; Figure 4-1). Soil moisture and drought indices, including the Palmer Drought Severity Index (PDSI), have been more strongly affected, indicating the importance of evaporation related to surface temperatures in the regional water balance (Dai et al. 2004). In contrast, the Siberian high pressure system has undergone substantial weakening over the past 20 years (Gong and Ho 2002; Panogiotopolous et al. 2005; D'Arrigo et al. 2005); a weaker Siberian high has been associated with increased precipitation in winter (Gong and Ho 2002). Instrumental records for winter snowfall indicate a slight positive trend (Figure 4-1), but records are generally less than 60 years in length and are often discontinuous; i.e. the recent increase may be within natural variation. Over the past 40-year period, mean annual temperatures in Mongolia have increased a total of 1.8° C, more than twice the global average, with winter warming of 3.6° C (Batima 2000). Global Circulation Models (GCMs) for Mongolia vary widely in their predictions for precipitation change with continued warming, including both overall increases and decreases depending on the model (Batima and Dagvadorj 2000).

Modern studies across northern China, Tibet, and Mongolia have shown regional differences in the relationship between temperature and moisture availability, with warm-wet conditions prevailing in eastern Mongolia and the eastern portions of north-west China, and warm-dry conditions prevailing farther west and north (Yang et al. 2008). Paleo-climatic studies across much of arid central Asia, from the Tibetan plateau to Inner Mongolia have revealed substantial differences in past climate variability as well. While much of arid central Asia experienced a warm period coincident with the 'Medieval Warm Period' in Europe and a cooling associated with 'Little Ice Age' (e.g. Esper et al. 2002; Holmes et al. 2007), there are regional differences in the timing of these events. For example, the northern and southern portions of the Tibetan Plateau experienced different episodes of warming, with northeastern Tibet warming from 800-1100 AD and the southern parts of the Plateau warming from 1150-1400 (Yang et al. 2001; Bao et al. 2003). Both warm-wet and cool-wet periods have been inferred from paleo-climatic records in regions surrounding Mongolia, including evidence for warm-wet and cool-dry conditions in much of neighboring western China over the last several thousand years (Wünnemann et al. 2006; Holmes et al. 2007), though evidence for warm-dry and cool-wet conditions in that region has also been presented (Zhane et al. 2007). In some instances both warm-wet and cool-wet conditions have been inferred for the same location over different periods during the Holocene (e.g. Feng et al. 2006).

Temperature changes in the recent several hundred to two-thousand years are well-documented in Mongolia through a series of tree-ring records and include a pronounced 'Little Ice Age' in the 19th century and generally warm conditions with some episodes of cooling during the 'Medieval Warm Period' in the 9th-14th centuries (Jacoby et al. 1996; D'Arrigo et al. 2000; D'Arrigo et al. 2001). At least two other studies have undertaken to develop an understanding of moisture balance in the region over this time period; however, they have very different temporal scales and resolution, are limited in their regional scope, and are contradictory to one another over some intervals. For example, a lake sediment and pollen-based aridity record from western Mongolia's Lake Telmen found both the 'Medieval Warm Period' and the 'Little Ice Age' (LIA) to be more humid than average (Fowell et al. 2003), while a moisture dependant tree-ring chronology from a nearby region in central Mongolia found that several periods within the LIA were comparatively dry (Davi et al. 2006). The annually resolved ~600 year tree-ring record is difficult to compare to the nearly 8000 year Lake Telmen record, which was examined at a resolution of one sample per ~200 years.

To better understand links between temperature and moisture availability in western Mongolia, and to develop a broader regional picture of changes over time, a diatom-based inference model for salinity (measured as specific conductivity) was developed and applied to six lake sediment cores from across Mongolia's western Valley of the Great Lakes. Changes in sediment composition were also evaluated using loss-on-ignition, grain-size analysis, and magnetic characterization. Diatom-based salinity reconstructions and changes in sediment composition were then compared with available temperature-sensitive tree ring records (D'Arrigo et al. 2001) and recent instrumental records (KNMI 2007) to examine links between temperature and moisture availability over the past 2000 years. Over the full period of record, consistent changes occurred across all lakes over several intervals; all showed a positive relationship between warm temperatures, as inferred from the nearby tree-ring chronology, and increased lake salinity. Increases in the input of sediment with large grain size, high inorganic content, and high magnetic susceptibility often occurred during cool intervals and may indicate an influx of terrestrial material from increased run-off and rising lake levels during these periods. Recent sediment records also showed a link between the instrumental record of warming temperatures, especially in winter, and increased lake salinity. Recent changes in diatom assemblages were, however, poorly correlated with the tree-ring record. Shifts in the diatom assemblages in the most recent decades are unique from those over those in the longer record, with a rapid rise in planktonic taxa that are often indicators of eutrophy, over the last approximately 15 years. Recent changes in the diatom assemblages in lake sediment cores were also correlated to rapid land-use change and must therefore be interpreted carefully.

Study Region

The Valley of the Great Lakes lies in far western Mongolia, bounded by the Altai Mountains to the west, the Khangai Mountains to the east, and the Gobi Desert to the south (Figure 4-2). The Great Lakes region is part of the internally drained Central Asian Basin; it also includes several smaller closed drainage basins with lakes ranging from fresh to hypersaline (Dulmaa 1979). Many of the large terminal basins in the valley are believed to be the remnants of large Tertiary or Quaternary paleo-lakes (Grunert et al. 2000). Local climate is harsh; the average annual temperature is near 0ºC, with long, cold winter months punctuated by hot, dry summers. Average annual rainfall is variable, with the most arid conditions (<100 mm yr^{-1}) in the valley bottom and slightly wetter conditions (300-400 mm yr^{-1}) in the Khangai Mountains to the east (Academy of Sciences MPR 1990).

The western part of the country is distant from the increasingly industrial and service-driven economy of the capital city of Ulaanbaatar and the economy of the region relies heavily on a pastoral tradition, for both subsistence and income. Changes in government support and herding norms since 1991 have led to a large increase in the number of animals in the region and have led to decreased mobility on the landscape, with more animals concentrated in smaller areas (Mearns 2004). This increased grazing intensity has negatively impacted the grasslands in many parts of Mongolia (Li et al.

2008; Sternberg 2008).

Methods

Sediment Cores and Dating

Sediment cores were obtained from six lakes (Figure 4-2) using a polycarbonate tube fitted with a piston and operated by rigid drive rods. Coring sites were selected in lakes with relatively simple basin morphology where a deep, flat region was easily identifiable with a hand-held acoustic depth finder. Zagas was a small lake with two deep basins separated by a shallow sill at high elevation in the Altai Mountains (Table 4-1). Baga was a small, shallow lake surrounded by sand dunes at relatively low elevation on the eastern edge of the Valley of the Great Lakes. Doroo lake was a large lake at high elevation in the Altai Mountains. Takhilt and Bayan lakes were located on the western flanks of the Khangai Mountains; both were relatively large and deep. Cores were sectioned in the field into 1-cm increments and stored in air-tight containers. In the laboratory, samples were homogenized and sub-sectioned for further analyses.

Age-depth models for the six sediment cores were based on a combination of ^{210}Pb-dating and AMS-^{14}C dating of charcoal (Dr. Tom Brown, Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory). ^{210}Pb was measured through its grand-daughter product ^{210}Po (Eakins and Morrison 1978) and the constant rate of supply (c.r.s.) model (Appleby 2001) was used to estimate age for five of the six lakes (Figure 4-2). The exception was Doroo Lake where variable and high activity made the detection of unsupported ^{210}Pb ambiguous below 4 cm depth. By applying a constant initial concentration model (Robbins 1978) ^{210}Pb dates were determined for these uppermost four intervals. Charcoal for AMS-^{14}C dating was picked from the sediment and then treated with an acid-base-acid rinse. A range of 1-3 AMS dates was obtained for each core with the number of dates constrained by the availability of charcoal and maximum estimated age of the core. Relatively large error bars on some AMS dates (Table 4-2) are due to a paucity of charcoal in the sediments. AMS-^{14}C dates were calibrated using CALIB 5.0 (Stuiver and Reimer 1993; Stuiver et al. 1999). Age-depth models were constructed using linear interpolation or exponential models for the ^{210}Pb dates and either linear interpolation or linear fits for the older portions of each core. All dates are given as calibrated calendar years AD.

Sediment Analyses

Organic, inorganic, and $CaCO_3$ composition was characterized for all cores, following the loss-on-ignition procedure outlined by Dean (1974). Isothermal Remanent Magnetization (IRM) and Anhysteretic Remanent Magnetization (ARM) were measured at the Institute for Rock Magnetism at the University of Minnesota. IRM was acquired in a magnetic field of 1500 mT and reflects the concentration of ferrimagnetic magnetic minerals. ARM was acquired in a peak alternating field of 100 mT and a bias field of 50 μT. All remanence parameters were measured with a cryogenic magnetometer (2G-model 760-R). To analyze grain size of clastic material, approximately 3.0 g of sediment were heated in 10% HCl for 15 minutes. Sediments were then digested in 30% H_2O_2 for 30 minutes (or until reaction ceased), and two mL of 11-M HNO_3 were added for 10 minutes. The samples were rinsed into centrifuge tubes with deionized water and methanol, and centrifuged at 4,500 rpm for 15 minutes. In order to minimize loss of sediment after rinsing, the supernatant was removed from the tubes using a sipper apparatus instead of being decanted (modified from Triplett 2002). Processed sediment was frozen until analysis, and grain size was measured using a Horiba LA-920 particle analyzer.

Statistical Analyses

Four variables (specific conductance, total phosphorus, bicarbonate, and lake morphology) have been previously identified as statistically significant and independent controls on the distribution of diatoms in regional lakes (Shinneman et al. in press). The inference model for specific conductivity was developed and the predictive ability assessed using a weighted-averaging approach with bootstrap error estimation in C^2 software (version 1.4.2; Juggins 2003). The strength of the model was assessed using the coefficient of determination (r^2=0.91) and the root mean square error (RMSE=0.15). Because the same data are used to generate and evaluate the model, the RMSE is not entirely independent and the validation step of bootstrapping with 1000 cycles was used to generate a bootstrapped coefficient of determination (r^2=0.81) and a root mean square error of prediction (RMSEP=0.39) which more realistically portrays error estimates (Fritz et al. 1999). Reconstructions were based on a weighted-averaging transfer function with classical de-shrinking (initial log SC = 1.2086 + 0.62294*observed log SC). Specific conductance was the most statistically significant variable in the training set, and was therefore used to develop the inference model, but it was linearly related to total dissolved solids (SC=1.315*TDS+141.92; r^2=0.99) and therefore can be considered analogous to salinity. In order to ensure fossil diatom assemblages had good analogues in the modern calibration set, the similarity between fossil and surface samples was assessed using the squared chord distance coefficient in the analogue package of R (R

Development Core Team 2006).

Tree ring records were used for comparison between diatom-inferred changes in lake salinity and regional temperature. Records were obtained from the International Treering Database maintained by the National Oceanic and Atmospheric Administration (NOAA) (D'Arrigo et al. 2001). Standard de-trended raw ring widths were used. Original publication of these records established their temperature sensitivity (Jacoby et al. 1996; D'Arrigo et al. 2001).

Instrumental climate variables (composite anomalies in winter and summer temperature, winter and summer precipitation) were compared with the diatom community changes in the recent ~60 years. Human influences affecting surface waters in the region have been documented, including concerns about rapid eutrophication (Chapter 3); historic livestock population data were also compared with changes in diatom communities to partial out variation due to recent eutrophication rather than changes in climate. Instrumental climate records were obtained from six weather stations in Western Mongolia (Hovd, Omno-Gobi, Altai, Baruunturuun, Tosentsengel, Uliastay) which are part of the publicly available Global Historical Climate Network (KNMI 2007). These stations have semi-continuous records of temperature and precipitation varying from 44 (Tosentsengel) to 70 (Hovd) years in length. Temperature and precipitation records for each station were standardized by subtracting the average series value from each data point and dividing by the standard deviation within that station record. These standardized values were averaged by season for each year, with June, July, and August making up the summer season and December, January, and February the winter season. Years missing more than one month of data per season were not used. The composite average deviation from the mean for all stations was used in variance partitioning. Local grazing records were not publicly available; national herd size from previously published records (Bold 1998; World Bank 2003; FAO 2007) was assumed to be proportional to local herd size.

Variance partitioning with partial constrained correspondence analysis (pCCA) was used to examine the relationship between changes in diatom communities and independent records of temperature from temperature sensitive tree-rings and instrumental climate data (Lotter 1998). Each centimeter section of sediment represented more than one year, with an average of 25 years per centimeter over the length of the cores. It was therefore assumed that diatom assemblages would reflect average conditions over the previous approximately 25 years and partial CCAs with tree-ring records used a 25-year running mean of tree-ring width for comparison. Because of higher recent sedimentation rates combined with less sediment compaction at the tops of cores, comparisons with recent tree ring widths, instrumental records, and changes in livestock numbers used a seven-year running mean of those variables over the period of instrumental record (1940-2005). A series of partial ordinations with each significant variable alone and each significant variable with other significant variables included as conditional co-variables was used to assess the unique and independent explanatory power of each variable. Detrended correspondence analysis (DCA) was used to assess the degree of floristic difference between diatom communities in different sections of the cores. All correspondence analyses were run using the vegan package of R software (R Development Core Team 2006).

Results

Sediment Records

Sediment accumulation rates varied from approximately 0.009-0.08 g cm^{-2} yr^{-1} (Table 4-1). Four of the lakes (Zagas, Bayan, Kholboo and Doroo) had sufficiently slow accumulation rates to preserve at least 2000 years of the sediment record in the 1-1.5 m cores. The diatom preservation in Takhilt lake was poor to absent below 90 cm, limiting the diatom-inferred salinity record to only the past 650 years of the 1000-year record in that lake. Higher sedimentation rates along with poor diatom preservation constrained the record in Baga to only the recent 100 years.

Diatom-inferred salinity over the past 2000 years

The five lakes with extended sediment records showed considerable variability in inferred salinity over the last 600 to 2000 years (Figure 4-4). General trends across all lakes included a small peak in salinity around 300-400 AD, a trend toward more saline conditions or a saline peak in 600-1000 AD, a pronounced freshening between 1000-1400 AD, a trend toward more saline conditions at approximately 1400-1600 AD, and fresher conditions for a short time in the 1800s to early 1900s. Inferred lake salinity was compared with tree-ring inferred records of warm and cool intervals over the past 2000 years (Figure 4-4; Table 4-3). Periods of extended above average temperature, including those between 600-1000 AD, 1400-1600 AD, and the warming from 1900 to today are times of increased inferred salinity while cooler intervals from 1000-1400 AD and 1600-1900 AD are times of freshening. Variance partitioning demonstrated that 9-14% of change in the diatom assemblages could be linked with changes in tree-ring width over the approximately 1800-year period of common record. The percentages of variance explained were low, but statistically significant in four of the five lakes (Table 4-3).

In both Kholboo and Bayan lakes, more saline intervals are characterized by decreased abundance of fragilarioid taxa such as *Pseudostaurosira brevistriata*, *Staurosira construens* varieties and *Staurosirella pinnata* (Figure 4-5). Moderate increases in several *Amphora* taxa, including *Amphora libyca* and *Amphora perpusilla*, along with increases in *Opephora* species in Kholboo, occurred during intervals inferred to be more saline. Doroo lake had increases in many of the same fragilarioid species during more humid intervals, though their overall abundance was lower than in Kholboo and Bayan. Fresher periods were also characterized by a greater abundance of *Puncticulata radiosa*. More saline intervals in Doroo are marked by increases in *Navicula salinarum*, *Fallacia pygmaea*, and several species of the genus *Nitzschia*, including abundant *Nitzschia bacillum*. A dramatic rise in the abundance and diversity of fragilarioid taxa, including *Staurosira construens* v. *venter*, *Pseudostaurosira pseudoconstruens*, and *Staurosirella pinnata* in the 1800s took place during the overall shift toward fresher conditions in Zagas at that time; the taxa showed minor increases in abundance during earlier fresh intervals as well. Saline intervals in Zagas were characterized by increases in *Opephora*, *Martyana*, and *Amphora* species. Takhilt was the most saline of the six lakes and had the highest proportions of salt-tolerant taxa such as *Chaetoceras*, *Amphora*, and *Anomoeoneis*, which became more abundant in the most saline intervals. Relatively fresh intervals in Takhilt were characterized by increased proportions of *Cyclotella* species and fragilarioid taxa.

Comparisons of modern and fossil species assemblages species showed that fossil assemblages were well represented in the calibration set (Shinneman et al. in press). Squared chord distance between each fossil sample and its nearest analog in the calibration set was within the fifth percentile of the distance distribution within the calibration set (Bennion et al. 2004) except for the deepest five samples in Takhilt lake, which were within the tenth percentile. These distributions indicate insignificant floristic differences between fossil samples and their nearest analogue in modern samples.

Sediment records over the past 2000 years

Sediments in Doroo, Kholboo, Takhilt, and Zagas lakes were dominated by the inorganic fraction (67-73%), Bayan was dominated by carbonate sediment for much of the record, and sediments in Baga were predominantly organic (Figure 4-7). Proportions of the sediment constituents are remarkably stable throughout the record in Doroo and Kholboo lakes. Zagas and Bayan lakes were more variable throughout the sediment record, with greater fluctuations between the inorganic and carbonate fractions of the sediment. Takhilt Lake had a highly variable record with rapid swings between carbonate and inorganic dominance in the sediment. Organic matter content increased overall throughout the record in Takhilt, but was also highly variable. Baga had very high organic sediment accumulation from 1400-1600 AD, with the exception of a sharp decrease in organics and increased inorganic inputs for a short time around 1500 AD. Common periods of change in all cores included a time of high organic matter content and reduced inorganic content between about 1600 and 1800 AD in all lakes except Zagas, where a similar pattern occurs just prior to 1600 AD. High organic content and lower inorganic content also occurred in most lakes for a short period around 1200 AD.

The IRM (concentration of magnetic particles) was 1-2 orders of magnitude greater in the western lakes (1.2e^{-2} -2.8e^{-3} Am^{2} kg^{-1}) as compared to the eastern and central lakes (1.0e^{-4} – 6.0e^{-5} Am^{2} kg^{-1}). In Bayan, Kholboo, Doroo, and Zagas, magnetic properties were relatively stable throughout the record, while they were highly variable in Baga and Takhilt (Figure 4-7). At four of the six sites increases in the concentration of magnetic minerals were accompanied by significant decreases in ARM/IRM (i.e. larger ferrimagnetic particles; Banerjee et al. (1981)) whereas at Kholboo and Baga there was a positive correlation (e.g. smaller particles). Changes in the ratio of ARM/IRM are used to characterize the relative importance of fine magnetic particles compared to larger particles; ARM is strongly influenced by the presence of small single-domain (SD) and small pseudo-single-domain (PSD) particles (Hunt et al. 1995). Across the region, recent sediments were characterized by a doubling in IRM since 1900 AD.

Increases in the mean and median grain size in all five lakes are generally in-phase with increases in susceptibility, although the magnitudes of the changes were not always well matched; changes in grain size were both in- and out-of-phase with changes in magnetic grain size parameters in different lakes. Increases in mean and median grain sizes occurred in all lakes at approximately 1600 AD, in all lakes except for Doroo and Kholboo at 1300 AD, in all lakes at 900-1000 AD, and in all lakes except Doroo at 200-400 AD.

Diatom-inferred salinity and the instrumental record

Recent, more highly resolved records showed fairly stable values for inferred salinity over much of the past 100 years (Figure 4-6). Conditions in all lakes were generally saline compared with the two-thousand year record with especially high inferred salinity in Doroo and Bayan (Figures 4-4 and 4-6). All lakes except Doroo showed a peak or increase in salinity in the early 1980s. In Zagas this trend toward increasing salinity continued while other lakes became briefly less saline before salinity increased again in the late 1990s. Peaks in salinity occurred in two lakes, Kholboo and

Takhilt, in the mid 1920s; this is before the availability of regional instrumental records. Other recent saline excursions (1950s, 1980s, and 1990s to today) correspond temporally with prolonged above average deviations in both summer and winter temperature (Figure 4-6).

Over the period of instrumental record (1938-2005) variance partitioning demonstrated that changes in one or more measured climate variables were significantly explanatory of changes in the diatom assemblages in five of the six lakes. Due to very slow sedimentation rates limiting sample resolution and suspect dating at the top of the core, Doroo lake was excluded from recent statistical analyses. Winter temperature was the most significant climate variable in three of the five lakes, with summer temperature the most significant in Bayan Lake and both summer and winter temperature having similar explanatory power in Takhilt Lake (Table 4-4). Tree-ring records for this period showed decreased correlation with changes in diatom community assemblages compared to the 2000 year records. Variance partitioning indicated an insignificant fraction of variance in diatom communities over the past 60 years could be linked with changes in the tree-ring record (Table 4-4).

Because the landscape over recent years has experienced significant effects of heavy grazing (Li et al. 2008; Sternberg 2008; Chapter 3) the effects of landscape change and increased nutrient flux may confound records of diatom-inferred climate in the lake sediment records. Shifts in diatom assemblages were therefore also compared with livestock population records over the recent approximately 60 years. Changes in livestock population were also significantly related to community shifts in all lakes. Not all climate and livestock variables that were significant individually remained significant when the interactive effects with other potential explanatory variables were taken into account (Table 4-4).

Diatom assemblages representing the most recent 5-15 years are markedly different than those from the deeper core intervals. While small planktonic diatoms, often indicators of eutrophic lake conditions, are nearly absent from the records before the 1990s, most lakes had a large increase in the population of diatoms such as *Stephanodiscus minutulus*, in the last decade (Figure 4-5). A DCA, which separates samples by the variation in the diatom assemblages, showed that most lakes had distinct groups corresponding to major shifts in salinity over the 2000 years of the core; however, in all lakes except Kholboo, a number of recent samples (1990-2005) stand apart, unlike any previous diatom assemblage. In the shorter but more highly resolved record from Baga lake, a clear division can be seen in the diatom communities in the pre-Soviet era when livestock population and movements were heavily regulated, and the communities in the post-Soviet free-market era when grazing intensity increased, with a transitional sample between (Figure 4-8).

Discussion

Temporal and statistical links between diatom-inferred salinity and independent temperature records indicated a positive relationship between warming temperatures and increased lake salinity. Variance partitioning demonstrated that changes in diatom communities over the past approximately 2000 years were significantly correlated with temperature records inferred from a regional tree-ring width chronology. Changes in sediment input to the lakes was highly variable across the region and over time; most lakes preserved some periods of increased terrestrial sediment inputs during extended cool intervals, likely indicating increased run-off and rising lake levels. Variance partitioning using instrumental records in the most recent 60 years showed the strongest link between changes in diatom communities and increased winter temperature, and to a lesser extent summer temperature and precipitation. Recent changes in diatom assemblages were poorly correlated with changes in tree ring widths but significantly correlated to changes in livestock population.

Inferred climate shifts over the past 2000 years

Relatively short temperature excursions from the tree-ring record were not always reflected, or not always reflected consistently, in the long-term record of diatom-inferred salinity. This may be due to the low sampling resolution in the diatom records compared to the annually resolved tree ring records. It may, however, reflect a lag time in lake response or a threshold of temperature change which needs to be surpassed before the lakes, and thereby the diatom communities, are strongly affected. The most extended warm and cool intervals (e.g. 600-1000 AD and 1100-1400 AD, respectively) were periods with the most significant shifts in diatom-inferred salinity and also times where changes in sediment composition showed pronounced and synchronous shifts across the region. Alternatively, differences among sites on shorter time scales may reflect the regionally heterogeneous climate as underscored by Batima (2006) who reported a mix of both increases and decreases in precipitation at weather stations in northwestern Mongolia over the past 30 years. Previous research into long-term climate shifts over the course of the Holocene observed major north-south differences in the timing and direction of climate changes for lakes in north central Mongolia over the past 12,000 years (Dorofeyuk and Tarasov 1998). Higher resolution studies and continued monitoring efforts are imperative to resolve the responses of these systems on shorter time scales.

Variance partitioning over the approximately 1800 years of common record showed a significant, but small, percentage of the variability in diatom communities was linked to changes in tree-ring variability. While both tree-ring growth and changes in diatom communities reflect local and regional climate to some degree, many additional factors contribute to the growth and community structure of both trees and diatoms and they should not be expected to co-vary precisely. The tree-ring record used here is from Tarvagatay Pass, a region approximately 125 km from the easternmost lake sites, and over 250 km from sites in the Altai Mountains. Whereas climate changes across all of western Mongolia can be considered similar over decades to centuries, differences in the timing and magnitude of sub-regional warm and cool years is possible and may contribute to the relatively small amount of variance explained. Tree-ring studies of recent, higher-frequency change in the more humid forested regions of eastern and central Mongolia have also linked stream flow with broad scale climatic patterns like the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and solar variability on decadal to multi-decadal time scales (Davi et al. 2004; Pederson et al. 2001) indicating many more subtle high frequency processes may be at work than can be identified here. Variance partitioning in the most recent record indicated winter temperature was one of the most influential variables linked to changes in diatom communities; however, the long-term tree ring record reflects growing season temperatures. A proxy for past winter temperature may give a stronger correlation with community changes over the longer record if past warming and present warming are analogous.

Higher resolution records over the most recent 60 years had much lower correlation with changes in the tree-ring record; a significant relationship was found only in Baga lake. The decreased correlation in the recent record compared to the longer record could also point to non-analogous warming between past warm periods and modern warming. Recent warming is predominantly in the winter season. Increased winter temperatures have led to earlier ice-free season (Batima and Dajvadorj 2000), thus increasing the period of the year during which lakes and pools might lose water through evaporation. In larger lakes, in particular, a longer ice-free season can also alter the timing of summer stratification and change the rate of temperature increase (Austin and Coleman 2007). Higher correlation between past changes in diatom assemblages and changes in growing season as reflected in the tree ring records may indicate past warming events were more pronounced during the growing season, and salinity increases were related to slightly different mechanisms, such as increased evaporation over the summer months.

Sediment composition can often provide an additional proxy for changes in local moisture balance. Lake sediments have been shown to have increased concentration of magnetic minerals and an increased proportion of clastics and magnetically coarse-grained material when terriginous inputs are high such as during times of increased precipitation and run-off (Geiss et al. 2004). Regional lakes generally preserved increased concentration of magnetic particles, as measured by susceptibility, coincident with increases in mean and median grain size and increased proportions of inorganic sediment content. This pattern occurred during several intervals which coincide with cool periods in regional tree ring records (~900, 1300, 1600-1700 AD). These increases in allocthonous inputs could indicate increased lake level and greater shoreline erosion, or increased upland erosion and river or overland transport of sediment, or a combination of the two. There is also a common pattern of increased organic content with a relative decrease in inorganics during several of the major warm periods in the record. The shifts are often subtle and are not of the same magnitude in all warm intervals. Overall, changes in sediment lithology during prolonged warm and cool intervals support the finding of increased moisture availability during cool intervals, though other factors are likely confounding the climate signal in many lakes.

Inferred climate and land-use shifts in recent decades

Weighted-averaging models assume that the diatom communities are responding solely to a single modeled environmental variable, disregarding correlations to other variables (Bennion et al. 1996). Salinity is the dominant gradient in the calibration set (Shinneman et al. in press); however, there is also a strong secondary gradient in total phosphorus (TP). When multiple factors strongly influence diatom assemblages, diatom-inferred changes need to be evaluated carefully. A transfer function has been previously developed for total phosphorus (Shinneman et al. in press) and changes in diatom-inferred salinity and diatom-inferred TP are moderately well correlated in three of the five cores (Table 4-6). While saline intervals in the past were not times of increases in typical eutrophic lake planktonic taxa such as *Stephanodiscus minutulus*, recent core intervals have large increases in *Stephanodiscus* and other planktonic taxa (Figure 4-5; Chapter 3). Such differences in the species responses to increased salinity and increased nutrients may allow for both variables (SC and TP) to be inferred through changes in sub-sets of the diatom community. However, some species may respond to both elevated salinity and elevated nutrients, causing the recent eutrophication to lead to spurious increases in modeled salinity (Anderson 2000).

The correlation between diatom-total phosphorus and diatom-inferred salinity in recent decades may be real; loss-on-ignition records indicated higher productivity during warm periods and fluxes of sediment phosphorus and biogenic silica have been previously shown to have increased in some lakes during the most extended warm intervals between 600-1000 AD and between 1700-1800 AD (Chapter 3). It is also possible, however, that the correlations are due to the diatom community response to one variable causing a spurious change in the other variable in the model. Livestock population was significantly correlated with changes in diatom community in the recent 60 years. Fluctuations in livestock population prior to the early part of the 20th century are poorly known or documented; however, the rate of change and number of livestock on the landscape in recent decades is thought to be unprecedented in Mongolian history (Bold 1998). While changes in diatom communities related to changing nutrient flux over the past several thousand years is possible, the degree to which lakes are responding to nutrient enrichment today is likely unprecedented.

Detrended correspondence analysis showed that the diatom communities in the uppermost intervals of all lakes except Kholboo were significantly different than lower core samples, possibly an indication that the major driver of the system has shifted, or at least become modified with recent nutrient impacts. Kholboo lake, located in a government ‘Protected Area’, is the most distant of the six lakes from roads and settlement and would therefore likely be the least impacted by increased grazing intensity. The variance explained by tree rings is significantly lower within the last 100 years than over the entire 2000-year record, again indicating that perhaps the driving mechanism has shifted. Recent eutrophication has been recognized in other lakes in surrounding regions, where it has also been posited that human impacts may be altering the affects of climate signals in the lake sediments (e.g. Wünnemann et al. 2006). The difficulty of separating human impacts from climate signals in lake records has also been noted in other parts of the world (e.g. Heiri and Lotter 2005; Itkonen and Salonen 1994). Records can likely be interpreted mainly in terms of changing salinity prior to the last 20 years, but recent changes are subject to multiple and complex interpretations.

Long-term human-climate interactions

Climate has been identified as a major contributor to the development and evolution of nomadic cultures throughout the central Asian region (Dirkson et al. 2007; Van Geel et al. 2004). A very consistent freshening occurs in all lakes between about 1000-1200 AD. An abrupt change to more saline conditions occurs at around 1220 in all lakes except Kholboo, where the transition is dated to 1330 (with a dating error of 120 years). This abrupt change to saline conditions coincides with the main expansion of the Mongol empire in the 13th century. The first westward expansion to Europe and the

Middle East took place in 1219 and major campaigns continued through the middle of the 13th century (Weatherford 2004).

Previous study of charcoal in Mongolian lakes noted the very low flux of charcoal to lake sediments during most of the last two thousand years (Umbanhower et al. in press). One notable exception was a period of high charcoal influx to regional lakes between about 1200 and 1500 AD. This was a relatively arid interval in our records; however, it was neither the longest arid excursion nor the most consistent among the lakes; it did, however, follow the longest extended humid period. This may indicate the importance of fuel-limitations on wildfires; the increased vegetation growth from the humid period provided unusually large availability of fuels for wildfires when drier conditions returned.

Previous research has speculated generally on the role of the warm interval in the 13th century in contributing to the expansion of the Mongol Empire. While warmer than average conditions could be seen as an advantage to the travels of the Mongolian army (D'Arrigo et al. 2001), others have speculated that the increased warmth may have triggered drought conditions, forcing the expansion of the empire in order to expand grazing lands (Fagan 2008), an inference that is in agreement with the records established here. In addition, the previous extended cool and moist time period may have supported increased populations of animals and humans which were subsequently put under pressure when arid conditions decreased soil moisture, made surface waters more saline, and perhaps increased fire frequency.

Conclusions

Over 50% of rural herders in Mongolia lack access to improved water sources, relying instead on natural sources for their household water supply and to support animal herds. This reliance increased after 1990 as the number of improved wells in the country decreased substantially following the end of the Communist era (Batbold et al. 2004; Sternberg 2008). At present, nearly 20% of surface water bodies in Mongolia are permanently saline with a larger portion of these in the western and southern regions (Batbold et al. 2004). As temperature increases continue, increased evaporative losses in this arid region are likely.

Understanding long-term patterns and variability in effective moisture balance is critical to planning and management of water resources as well as to an accurate understanding of paleo-climatic conditions and future climate modeling. Globally, many regions are facing water crises (Oki and Kanae 2006) increasing our need to understand long-term hydrologic variability, especially in arid regions. In many parts of the world, water resources planning has been based on short-term trends in climatic data and water managers are now confronted with changes in moisture balance beyond that which has been previously experienced or planned for (e.g. Schindler and Donahue 2006). While further research is needed to refine our understanding of the climatic and hydrologic systems in Mongolia, evidence presented here suggests that increased drought conditions and salinization of surface water bodies is likely with increased warming. In particular, the increased warming in winter may be non-analogous to past warming, leading to environmental conditions that are unique in recent geologic history. This, combined with cultural eutrophication and the effects of overgrazing on vegetation in the region, may have a profound impact on ecologic and economic health in the region.

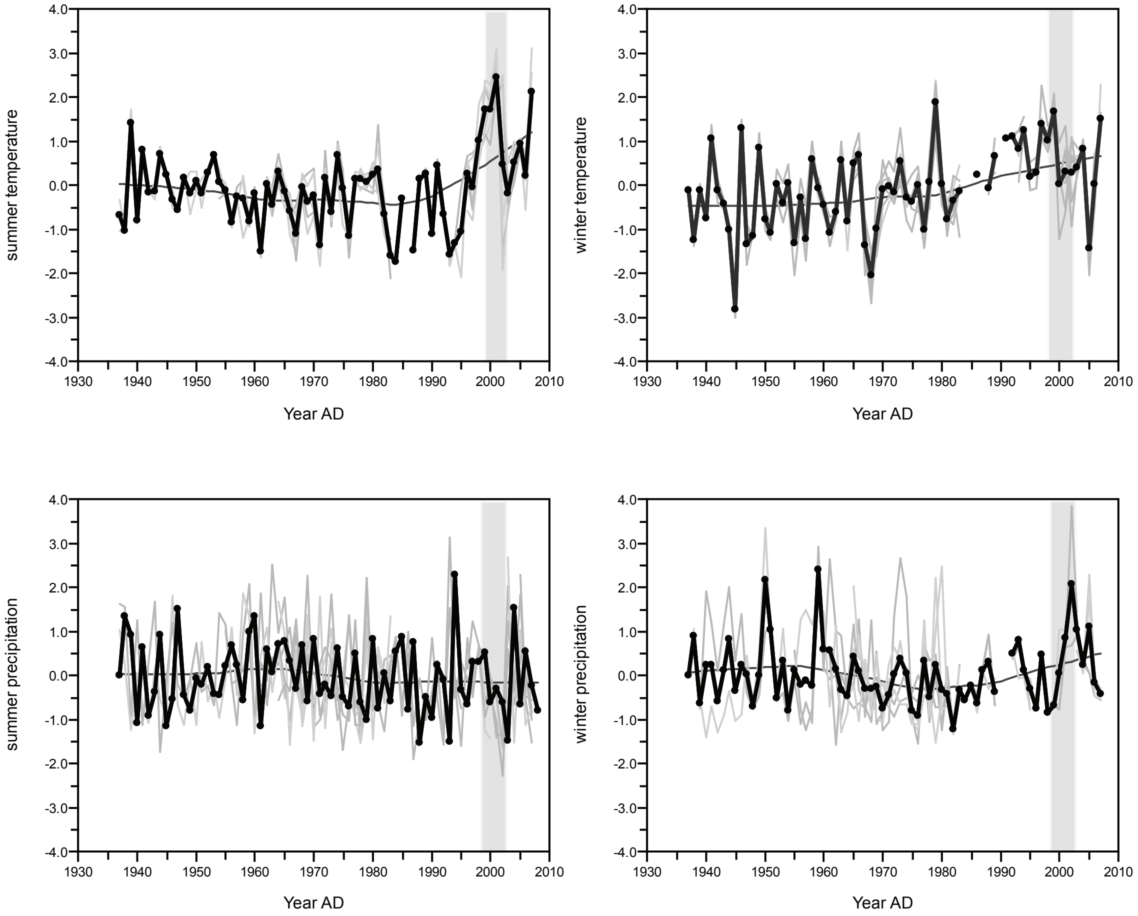


Figure 4-1: Weather station records from the Global Historical Climate Network (GHCN) (KNMI, 2007). The composite records (the average anomaly from six stations) is shown as a dark line with points for each sample, each station record individually is shown as a lighter grey line. Regional temperature anomalies are similar across all six stations, while precipitation is more variable from site to site. Recent *dzud* years (shaded) are clear in the precipitation records with summer drought followed by heavy snowfall. The solid horizontal line is a LOWESS smooth (span=0.45).

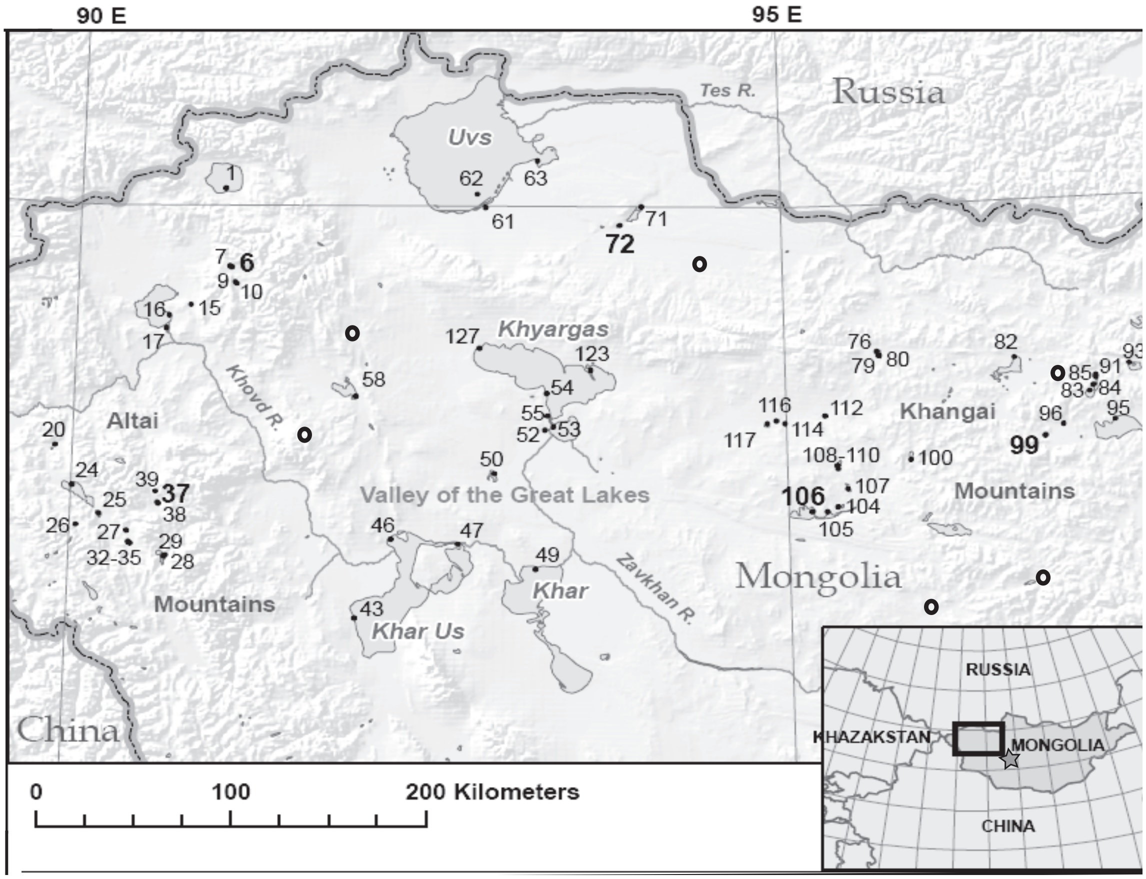


Figure 4-2: Map of study area. Numbers correspond to all sites surveyed for the regional calibration set (Shinneman et al., in press). Lakes cores for reconstructions were Kholboo (7), Doroo (29), Zagas (37), Baga (72),Takhilt (99), and Bayan (106). Open circles indicate the location of regional weather stations (Figure 4-1). The star in the inset map indicates the location of the tree-ring chronology.

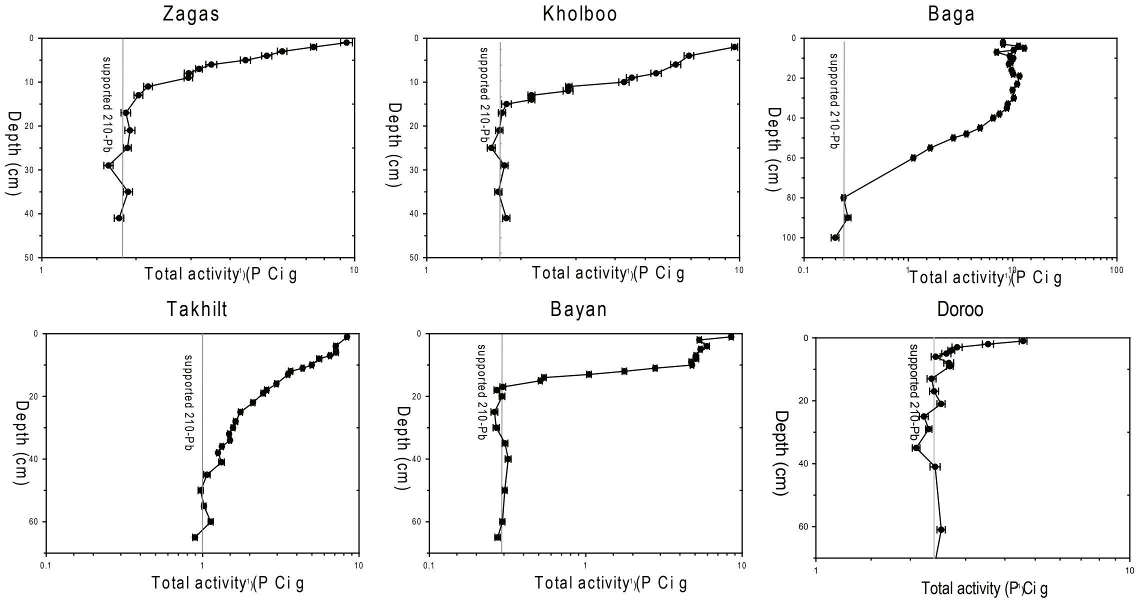


Figure 4-3: 210-Pb activity profiles

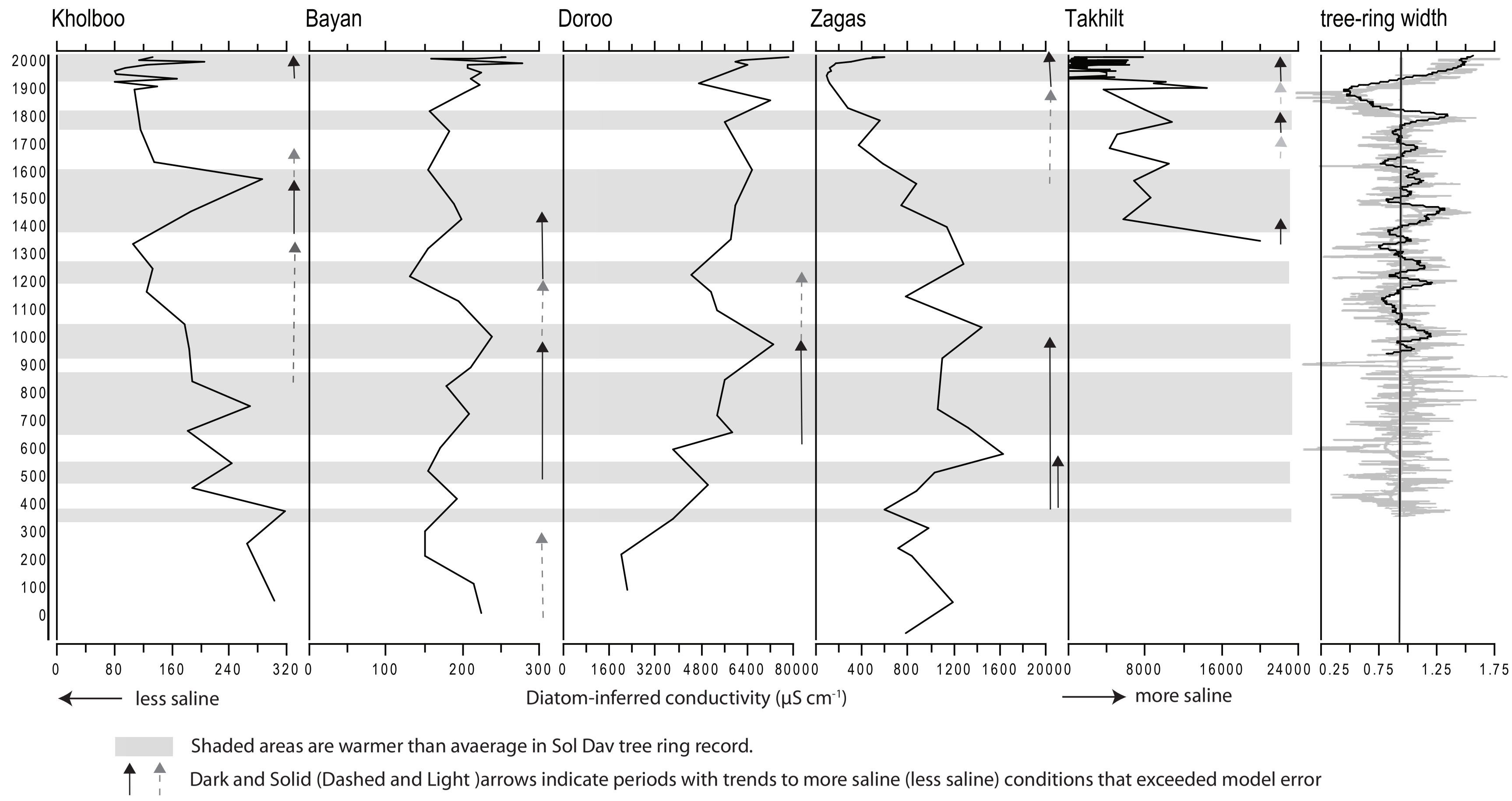


Figure 4-4: Diatom-inferred salinity (line) and warm (shaded)/cool intervals from the tree ring record. Arrows indicate changes to more saline (dark arrow) or less saline (light arrow) that exceed the error of the inference model. The dark line in the tree-ring record is the 25-year running mean of tree-ring data available in the NOAA database, the more extended record (in grey) is re-drawn from D'Arrigo et al., 2001.

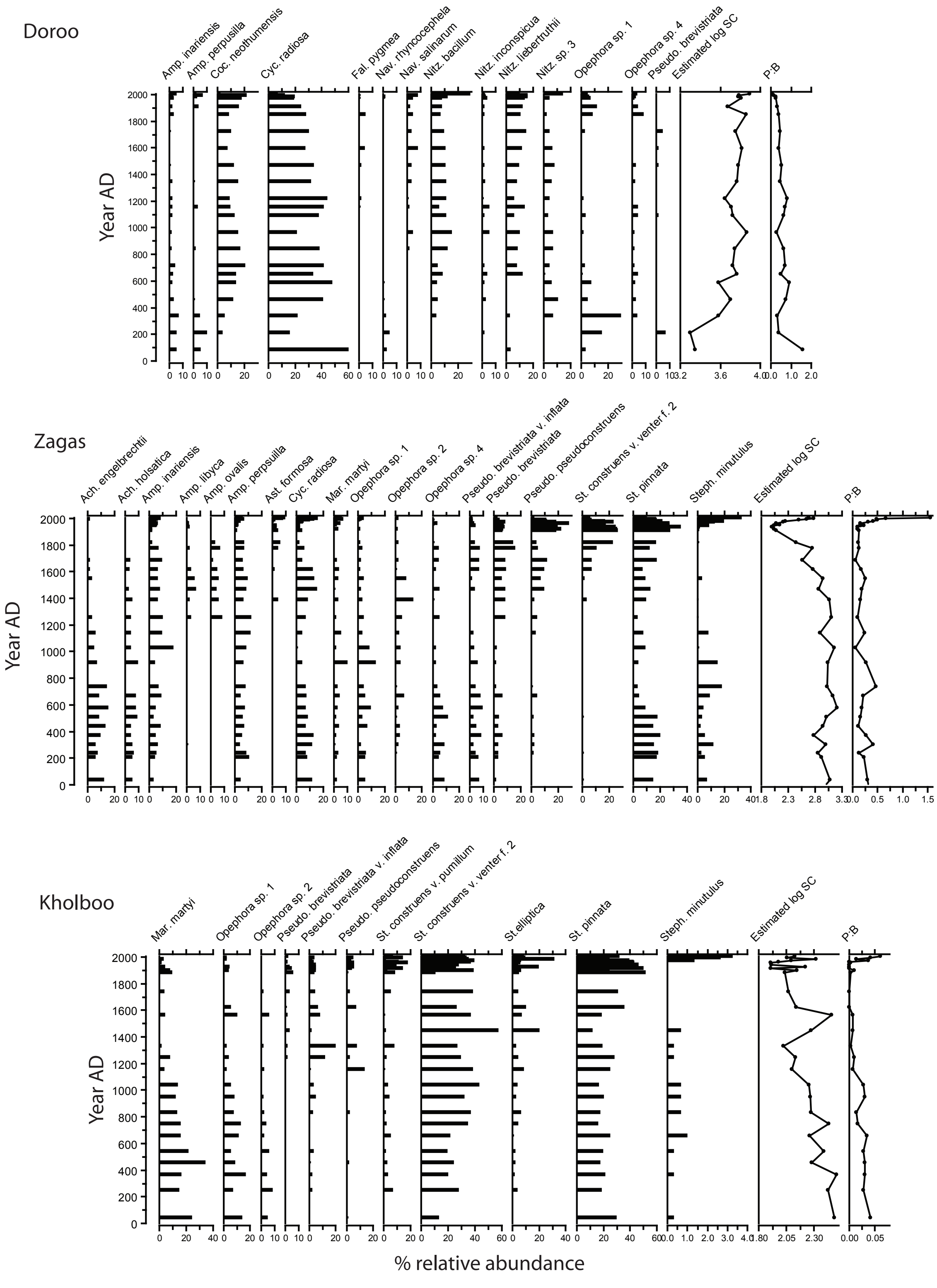


Figure 4-5: Diatom stratigraphic profiles for the most abundant diatoms (over 5% relative abundance in at least two intervals) in Doroo, Zagas and Kholboo (a) and Bayan, Takhilt, and Baga (b); time scales differ for Takhilt and Baga lakes.

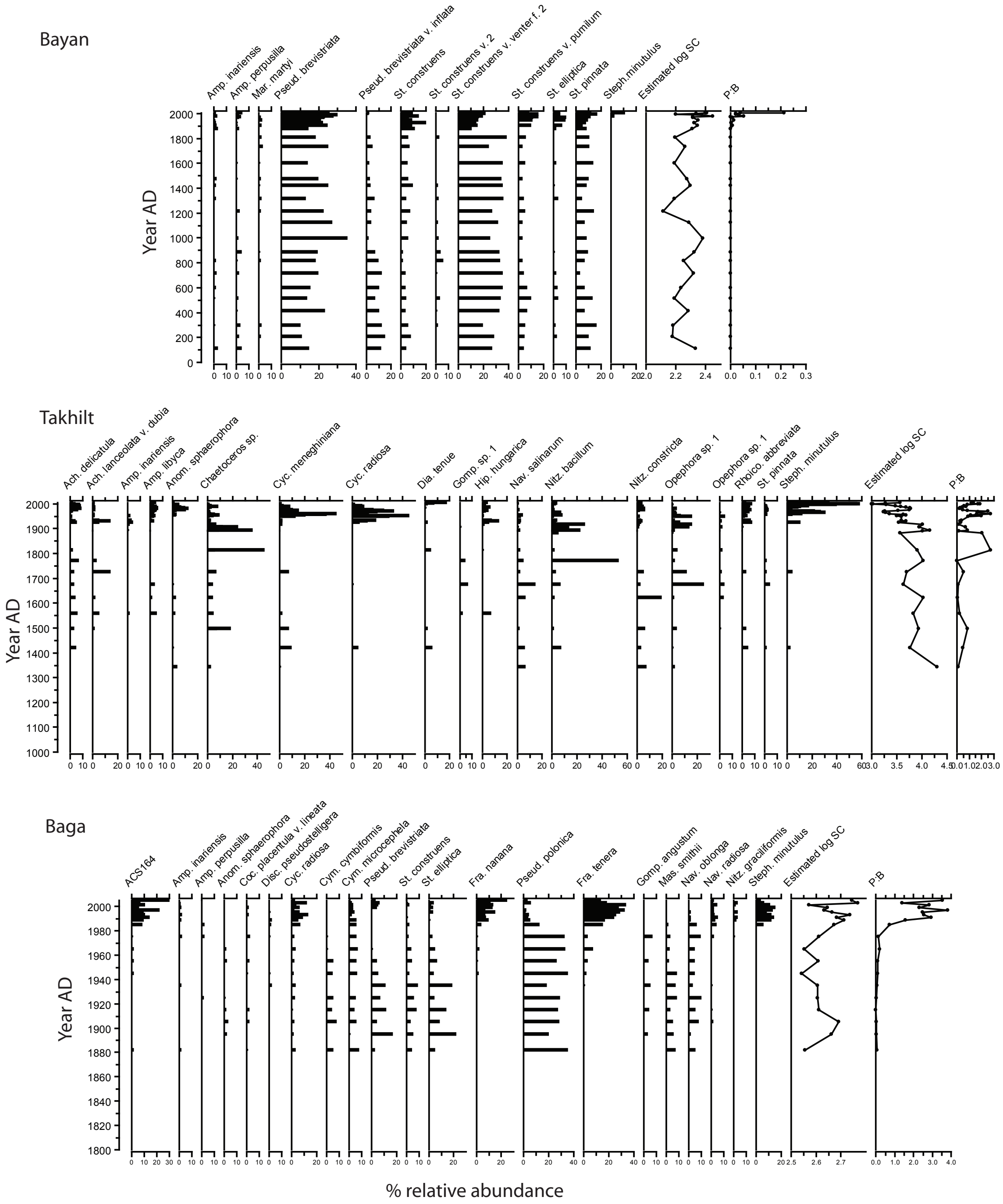

Bayan
Amp. inariensis
Amp. perpusilla
Mar. martyi
Pseud. brevistriata
Pseud. brevistriata v. inflata
St. construens
St. construens v. 2
St. construens v. venter f. 2
St. construens v. pumilum
St. elliptica
St. pinnata
Steph.minutulus
Estimated log SC
P:B
Year AD
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2.0
2.2
2.4
0.0
0.1
0.2
0.3
Takhilt
Ach. delicatula
Ach. lanceolata v. dubia
Amp. inariensis
Amp. libyca
Anom. sphaerophora
Chaetoceros sp.
Cyc. meneghiniana
Cyc. radiosa
Dia. tenue
Gomp. sp. 1
Hip. hungarica
Nav. salinarum
Nitz. bacillum
Nitz. constricta
Opephora sp. 1
Opephora sp. 1
Rhoico. abbreviata
St. pinnata
Steph. minutulus
Estimated log SC
P:B
Year AD
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
3.0
3.5
4.0
4.5
Baga
ACS164
Amp. inariensis
Amp. perpusilla
Anom. sphaerophora
Coc. placentula v. lineata
Disc. pseudostelligera
Cyc. radiosa
Cym. cymbiformis
Cym. microcephela
Pseud. brevistriata
St. construens
St. elliptica
Fra. nanana
Pseud. polonica
Fra. tenera
Gomp. angustum
Mas. smithii
Nav. oblonga
Nav. radiosa
Nitz. graciliformis
Steph. minutulus
Estimated log SC
P:B
Year AD
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
1800
2.5
2.6
2.7
0.0
1.0
2.0
3.0
4.0
% relative abundance

Figure 4-5 (b)

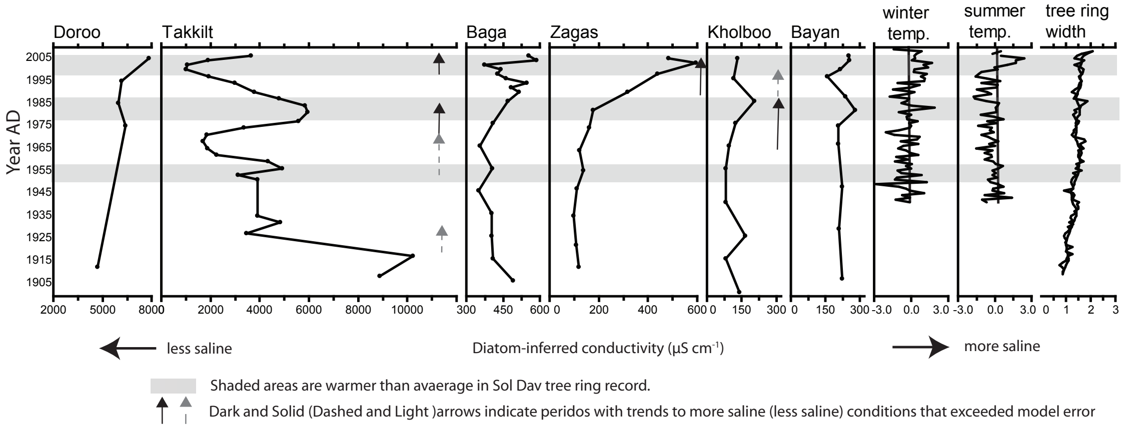


Figure 4-6: Diatom-inferred salinity (line) and warm/cool intervals from the instrumental record (shaded). Arrows indicate changes to more saline (dark arrow) or less saline (light arrow) that exceed the error of the inference model. The annual tree-ring record and the 7-year running mean of tree-ring data are given.

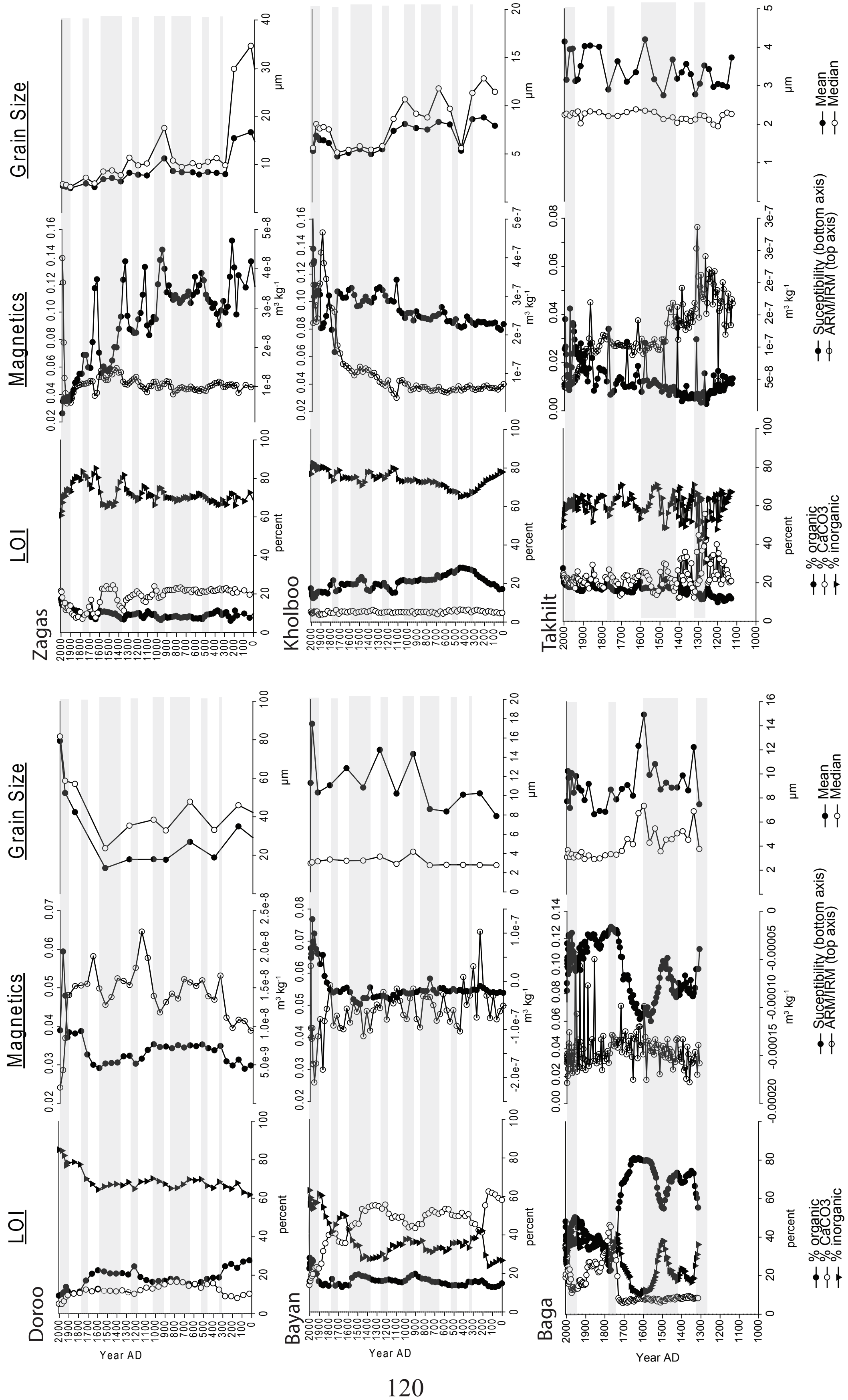


Figure 4-7: LOI, magnetic, and grain size profiles. Shaded intervals represent warm intervals in the tree-ring record.

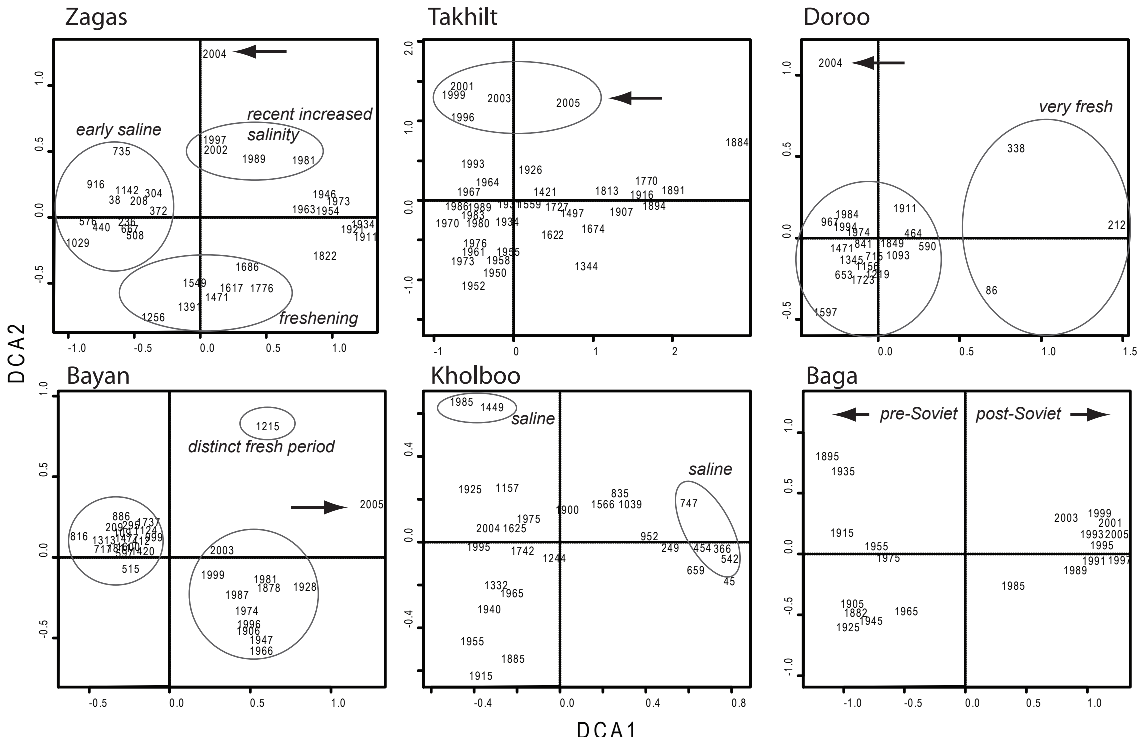


Figure 4-8: Detrended correspondence analysis for the six cores. Note that the most recent samples (arrows) in four of the six lakes (Zagas, Takhilt, Doroo, and Bayan) are distinct from lower core intervals. In Kholboo, the most remote of the six lakes, this distinction is not clear. In Baga lake, samples from the period of more heavily regulated grazing in the Soviet era are distinct from more recent samples.

Site #	lake name	site lat.	site long.	elev (m)	water depth (m)	core length (m)	SC (µS cm^{-1})	max. age (cal yr BP)	avg. accum. rate (g cm^2 yr^{-1})
6	Kholboo	49.7	91.1	2570	2.9	0.91	69	3120	0.007
29	Doroo	48.2	90.7	2394	9.1	1.16	4543	6994	0.009
37	Zagas	48.5	90.6	2376	8.7	1.55	473	5791	0.020
72	Baga	49.9	93.8	981	7.1	1.56	977	645	0.023
99	Takhilt	48.8	96.8	1841	5.4	1.52	3370	818	0.084
106	Bayan	48.5	95.2	1481	11.6	1.7	3092	3092	0.005

Table 4-1: Location and summary information for the six lakes

Lake	CAMS	Depth	14C age	Error	Cal Range*	Med Prob.
Kholboo	113768	68-72	1800	120	1576-1868	1727
	112152	84-85	2875	80	2877-3086	3002
Doroo	132980	22-27	1425	70	1273-1387	1329
	113011	84-87	4120	80	4530-4816	4658
	113010	112-113	6220	340	6712-7443	7443
Zagas	112153	87-88	1835	70	1700-1868	1770
	113770	139-143	4250	140	4568-4972	4795
Baga	126411	150-153	640	180	513-728	610
Bayan	132982	67-72	2050	45	1903-2128	2000
	129274	155-160	2875	50	2864-3198	3000
Takhilt	132983	84-88	475	35	450-558	510
	126410	139-143	850	120	681-909	770

Table 4-2: Charcoal dates

LAKE	% VARIANCE EXPLAINED	P-VALUE
Kholboo	8.6	0.06
Bayan	10.9	p≤0.01
Doroo	13.5	p≤0.01
Takkilt	12.8	p≤0.005
Zagas	10.2	p≤0.01

Table 4-3: Results of variance partitioning between extended records of diatom records and the tree ring chronology (25-year mean).

		%variance explained	significance
Kholboo			
animal pop.			
	total	33%	p≤0.05
	unique	19%	p≤0.01
winter temp.			
	total	34%	p≤0.01
	unique	20%	p≤0.1
tree-ring 7-year avg.			
	total	7%	--
Baga			
animal pop.			
	total	28%	p≤0.005
	unique	6%	--
winter temp.			
	total	38%	p≤0.005
	unique	16%	p≤0.01
tree-ring 7-year avg.			
	total	31%	p≤0.005
Zagas			
animal pop.			
	total	24%	p≤0.1
	unique	10%	--
winter temp.			
	total	35%	p≤0.005
	unique	21%	p≤0.1
tree-ring 7-year avg.			
	total	20%	--

		%variance explained	significance
Takhilt			
animal pop.			
	total	22%	p≤0.005
	unique	5%	p≤0.1
winter temp.			
	total	21%	p≤0.005
	unique	5%	--
summer temp.			
	total	13%	p≤0.005
	unique	6%	p≤0.1
winter precip.			
	total	10%	p≤0.05
	unique	7%	p≤0.05
tree-ring 7-year avg.			
	total	9%	--
Bayan			
animal pop.			
	total	22%	p≤0.01
	unique	17%	--
summer temp.			
	total	19%	p≤0.1
	unique	14%	--
tree-ring 7-year avg.			
	total	19%	--

Table 4-4: Variance partitioning for recent record (1940-2005); Doroo Lake had too little sediment accumulation in the past 50-100 years to be used in the recent analysis.   A seven-year average of all variables was used in the comparison with changes in diatom assemblages.

Lake	*correlation*	*significance*
Bayan	0.178	
Takhilt	0.339	
Doroo	0.668	*p<0.005
Kholboo	0.730	*p<0.005
Zagas	0.736	*p<0.005

Table 4-5: Correlations between diatom-inferred SC and diatom-inferred TP using Kendall’s rank correlation.

References

Academy of Sciences MPR (People's Republic of Mongolia) (1990) Information Mongolia: The comprehensive reference source of the People's Republic of Mongolia. Oxford: Pergamon Press. 505p.

Aizen EM, Aizen VB, Melack JM, Nakamura T, Ohta T (2001) Precipitation and Atmospheric Circulation Patterns at Mid-Latitudes of Asia. International Journal of Climatology 21: 535-556.

Ameel JJ, Axler RP, Owen CJ (1993) Persulfate digestion for determination of total nitrogen and phosphorus in low-nutrient waters. American Environmental Laboratory October 1993: 1-11.

American Public Health Association (APHA), American Water Works Association and Water Pollution Control Federation (1985) Standard methods for the examination of water and wastewater. Washington, D.C.

Anderson NJ, Rippey B, Gibson CE (1993) A comparison of sedimentary and diatom-inferred phosphorus profiles: implications for defining pre-disturbance nutrient conditions. Hydrobiologia 253: 357-366.

Anderson NJ (2000) Diatoms, temperature and climatic change. European Journal of Phycology 35: 307-314.

Appleby PG (2001) Chronostratigraphic techniques in recent sediments. In: Last WM, Smol JP (eds). Tracking Environmental Change Using Lake Sediments; Volume 1: Basin Analysis, Coring, and Chronological Techniques. Dordrecht (The Netherlands): Kluwer Academic Publishers: 171-201.

Austin JA, Colman SM (2007) Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophysical Research Letters 34: L06604, doi:10.1029/2006GL029021.

Banerjee SK, King J, Marvin J (1981) A rapid method for magnetic granulometry with applications to environmental studies. Geophysical Research Letters 8: 333-336.

Banzragch, Ts. and Dorjsuren, D (2006) Handout for the environmental impact assessment experts. D. Myagmarsuren (ed). Supported by MNE of Mongolia and World Bank, Ulaanbaatar. 234pp.

Batima P, Dagvadorj D (eds) (2000) Climate Change and its impacts in Mongolia. JEMR Publishing Ulaanbaatar.

Batima P (2006) Climate change vulnerability and adaptation in the livestock sector of Mongolia: AIACC Project Report AS06. International START Secretariat, Washington D.C.

Batbold K, Tuul Z, Oyun B (2004) Access to water and sanitation services in Mongolia, a report to the United Nations Development Programme. Hiimori Printing Company, Ulaanbaatar.

Bao Y, Brauning A, Yafeng S (2003) Late Holocene temperature fluctuations of the Tibetan Plateau. Quaternary Science Reviews 2335-2344.

Bedunah DJ, Schmidt SM (2004) Pastoralism and protected area management in Mongolia's Gobi Gurvansaikhan National Park. Development and Change 35: 167-191.

Bennett EM, Carpenter SR, Caraco NE (2001) Human impact on erodable phsphorous and eutrophication: a global perspective. Bioscience 51: 227-234.

Bennion H, Juggins S, Anderson NJ (1996) Predicting epilimnetc phosphous concentration using an improved diatom-based transfer function and its application to lake eutrophication management. Environemntal Science and Technology 30 (6): 2004-2007.

Bennion H, Appleby PG, Phillips GL (2001) Reconstructing nutrient histories in the Norfolk Broads, UK: implications for the role of diatom-total phosphorous transfer functions in shallow lake management. Journal of Paleolimnology 26: 181-204.

Bennion H, Fluin J, Simpson, GL (2004) Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. Journal of Applied Ecology 41: 124-138.

Birks HJB, Line JM, Juggins S, Stevenson C, Ter Braak CJF (1990) Diatoms and pH reconstruction. Philosophical Transactions of the Royal Society London B 327: 263-278.

Bold B (1998) The quantity of livestock owned by the Mongols in the 13th century. Journal of the Royal Asiatic Society 8: 237-246.

Bondarenko NA, Guselnikova NE, Vorobyeva SS, Logacheva NF (1993) Species composition of planktonic diatom algae of Lake Baikal and biology of dominant species, p. 72–75. In: Fifth workshop on diatom algae: Diatom algae as indicators of the changes of climate and environment. Russian Academy of Sciences, Siberian Division, Irkutsk

Bradshaw EG and Anderson NJ (2001) Validation of a diatom-phosphorus calibration set for Sweden. Freshwater Biology 46: 1035-1048.

Brinson MM, Malvárez AI (2002) Temperate freshwater wetlands: types, status, and threats. Environmental Conservation 29: 115-133.

Carlson RE (1977) A trophic state index for lakes. Limnology and Oceanography 22 (2): 361-369.

Carvalho LR, Cox EJ, Fritz SC, Juggins S, Sims P, Gasse F, Battarbee RW (1995) Standardizing the taxonomy of saline lake *Cyclotella* spp. Diatom Research 10: 229-240.

Conley DJ (1998) An interlaboratory comparison for the measurement of biogenic silica in sediments. Marine Chemistry 63:39–48.

Conley DJ, Schelske CL (1993) Potential role of sponge spicules in influencing the silicon biogeochemistry of Florida lakes. Canadian Journal of Fisheries and Aquatic Science 50: 296–302.

Conley DJ, Schelske CL (2001) Biogenic silica. In: Smol JP, Birks HJB, Last WM [Eds.] Tracking Environmental Change Using Lake Sediments Volume 3: Terrestrial, Algal, and Siliceous Indicators. Dordrecht (The Netherlands): Kluwer Academic Publishers: 281–293.

Cremer H, Wagner B, Melles M, Hubberten H-W. (2001) The postglacial environmental development of Raffles Sø, East Greenland: Inferences from a 10,000 year diatom record. Journal of Paleolimnology 26: 67-87.

Cumming BF, Wilson SE, Hall RI, Smol JP (1995) Diatoms from British Columbia (Canada) lakes and their relationship to salinity, nutrients, and other limnological varaibles. Bibl. Diatomol. 31.

D'Arrigo R., Frank D, Jacoby G, Pederson N (1999) Spatial Response to Major Volcanic Events in or about AD 536, 934, and 1258: Frost Rings and other Dendrochronological Evidence from Mongolia and Northern Siberia. Climatic Change 42: 31-34.

D'Arrigo R, Jacoby G, Frank D, Pederson N, Cook E, Buckley B, Nachin B, Mijiddorj R, Dugarjav C (2001) 1738 Years of Mongolian temperature variability inferred from a tree-ring width chronology of Siberian Pine. Geophysical Research Letters 28: 543-546. Data archived at the World Data Center for Paleoclimatology, Boulder, Colorado, USA.

D'Arrigo R, Jacoby J, Wilson R, Panagiotopoulos F (2005) A reconstructed Siberian High index since AD 1599 from Eurasian and North American tree rings. Geophysical Research Letters 32: L05705, doi: 10.1029/2004GL022271.

Dai A, Trenberth KE, Karl TR (2004) Global variations in droughts and wet spells, 1900-1995. Geophysical Research Letters 25: 3367-3370.

Davi NK, Jacoby GC, Curtis AE, Baatarbileg N (2006) Extension of drought records for Central Asia using tree rings: West-Central Mongolia. Journal of Climate 19: 288-299.

Dean WE (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. Journal of Sedimentary Research 44: 242-248.

Dirkson VG, van Geel B, Koulkova MA, Zaitseva GI, Sementsov AA, Scott EM, Cook GT, van der Plicht J, Lebedeva LM, Bourova ND, Bokovenko NA (2007) Chronology of Holocene climate and vegetation changes and their connection to cultural dynamics in southern Siberia. Radiocarbon 49(2):1103-1121.

Dorofeyuk NI and Tarasov PE (1998) Vegetation and lake levels in Northern Mongolia in the last 12,500 years as indicated by data of pollen and diatom analyses. Stratigraphy and Geological Correlation 6:70-83.

Dorogostaïsky V (1904) Matériaux pour server á l'algologie du lac Baïkal et de son basin. Bulletin de la Société Impériale des Naturalistes de Moscou 18: 229-265.

Dulmaa A (1979) Hydrobiological outline of the Mongolian lakes. Int Revue ges Hydrobiol 64:709-736.

Eakins JD and Morrison RT (1978) A new procedure for the determination of lead-210 in lake and marine sediments. International Journal of Applied Radiation and Isotopes 29: 531-536.

Edlund MB, Soninkhishig N, Williams RM, Stoermer EF (2001) Biodiversity of Mongolia: Checklist of diatoms, including new distributional reports of 31 taxa. Nova Hedwigia 72:59-90.

Edlund M B, Williams RM, Soninkhishig N (2003) The planktonic diatom diversity of ancient Lake Hovsgol, Mongolia. Phycologia 42:232-260.

Edlund MB, Levkov Z, Soninkhishig N, Krstic S, Nakov T (2006) Diatom species flocks in large ancient lakes: the *Navicula reinhardtii* complex from Lakes Hövsgöl (Mongolia) and Prespa (Macedonia). In: Witkowski, A. [Ed.] Proceedings of the 18th International Diatom Symposium. Biopress Ltd., pp 61-74.

Environmental Protection Agency (EPA) (2000) Nutrient criteria technical guidance manual: lakes and resovoirs. EPA 822-B-00-001. 232p.

Environmental Protection Agency (EPA) (2001) Ambient water quality criteria recommendations: lakes and reservoirs in Nutrient Ecoregion IV. EPA 822-B-01-009.

Esper J, Schweingruber FH, Winiger M (2002) 1300 years of climatic history for Western Central Asia inferred from tree-rings. The Holocene 12(3): 267-277.

Fagan, B (2008) The great warming: climate change and the rise and fall of civilizations. Bloomsbury Press, New York, NY. 263 pp.

Feng, Z-D, An CB, Wang HB (2006) Holocene climatic and environmental changes in the arid and semi-arid areas of China: a review. The Holocene 16(1): 119-130.

Fernández-Giménez ME (2002) Spatial and social boundaries and the paradox of pastoral land tenure: a case study from postsocialist Mongolia. Human Ecology 30: 49-78.

Fernández-Giménez ME, Batbuyan B (2004) Law and disorder: local implementation of Mongolia’s land law. Development and Change 35: 141-165.

Food and Agriculture Organization of the United Nations (FAO), United Nations Childrens Fund (UNICEF), United Nations Development Program (UNDP) (2007) Joint food security assessment mission to Mongolia. Ulaanbaatar (Mongolia) 34 pp.

Fowell SJ, Hansen BCS, Peck JA, Khosbayer P, Ganbold E (2003) Mid to late Holocene climate evolution of the Lake Telmen Basin, North Central Mongolia, based on palynological data. Quaternary Research 59:353-363.

Fritz SC, Juggins S, Battarbee RW (1993) Diatom Assemblages of Lakes of the Northern Great Plains, North America; A Tool for Reconstructing Past Salinity and Climate Fluctuations. Canadian Journal of Fisheries and Aquatic Sciences 50: 1844-1856.

Fritz SC, Cumming BF, Gasse F, Laird KR (1999) Diatoms as indicators of hydrologic and climatic change in saline lakes. In: Stoermer EF, Smol JP [Eds.] The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, 482 pp.

Gälman V, Rydberg J, Sjostedt de-Luna S, Bindler R, Renberg I (2008) Carbon and nitrogen loss rates during aging of lake sediment: Changes over 27 years studied in varved lake sediment. Limnology and Oceanography 53 (3): 1076-1082.

Gasse F (2002) Diatom-inferred salinity and carbonate oxygen isotopes in Holocene waterbodies of the western Sahara and Sahel (Africa). Quaternary Science Reviews 21: 737–767.

Geiss CE, Umbanhower CE, Camill P, Banerjee, SK (2003) Sediment magnetic properties reveal Holocene climate change along the Minnesota prairie-forest ecotone. Journal of Paleolimnology 30:151-166.

Germeraad PW, Enebisch Z (1996) The Mongolian landscape tradition: a key to progress. The Netherlands: Germeraad and Enebisch, 130p.

Giorgi F, Whetton PH, Jones RG, Christensen JH, Mearns LO, Hewitson B, vonStorch H, Francisco R, Jack C (2001) Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings. Geophysical Research Letters 28 (17): 3317-3320.

Gong DY and Ho CH (2002) The Siberian High and climate change over middle to high latitude Asia. Theoretical and Applied Climatology 72: 1-9.

Grunert J, Lehmkuhl F, Walther M (2000) Paleoclimatic evolution of the Uvs Nuur basin and adjacent areas (Western Mongolia). Quaternary International 65: 171-192.

Gunin PD, Dgebuadse Yu, Martinson GG, Rumyancev VA, Zigz Z, Tsegmed Sh, Tserensodnom G [Eds.] Sevastyanov, D. V., Shuvalov, V. F. and Neustrueva, I Yu. (Responsible Editors) (1994) Limnology and Palaeolimnology of Mongolia (Limnologiya i paleolimnologiya Mongolii), St Petersburg: Nauka Publishers, 302 pp.

Gunin, PD, et al. (eds.) (1999) Vegetation Dynamics of Mongolia, Geobotany 26, Kluwer Academic Publishers, Dordrecht, The Netherlands: 238 pp.

Håkansson H (1993) Morphological and taxonomic problems in four *Cyclotella* species (Bacillariophycae).

Diatom Research 8(2): 309-316.

Håkansson H, Hajdu S, Snoeijs P, Loginova L (1993) *Cyclotella hakanssoniae* Wendker and its relationship to *C. caspia* Grunow and other similar brakish water *Cyclotella* species. Diatom Research 8: 333-347.

Håkansson H (2002) A compilation and evaluation of species in the general *Stephanodiscus*, *Cyclostephanos* and *Cyclotella* with a new genus in the family Stephanodiscaceae. Diatom Research 17 (1): 1-139.

Hall RI, Leavitt PR, Smol JP, Zirnhelts N (1997) Comparison of diatoms, fossil pigments and historical records as measures of lake eutrophication. Freshwater Biology 38: 401-407.

Hall RI, Leavitt PR, Quinlan R, Dixit AS, Smol, JP (1999) Effects of agriculture, urbanization, and climate on water quality in the Northern Great Plains. Limnology and Oceanography 44: 739-756.

Heiri O and Lotter AF (2005) Holocene and Lateglacial summer temperature reconstruction in the Swiss Alps based on fossil assemblages of aquatic organisms: a review. Boreas 34: 506-516.

Holmes JA, Cook ER, Yang B (2007) Climate change over the past 2000 years in Western China. Quaternary International. In Press:doi:10.1016/j.quaint.2007.10.013

Houghton JT, Ding Y, Griggs DJ, Noguer N, van der Linden PJ, Dai X, Maskell K, Johnson CA [Eds.] (2001) Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge.

Houk V and Klee R (2004) The stelligeroid taxa of the genus *Cyclotella* (Kützing) Brébisson (Bacillariophyceae) and their transfer to the new genus *Discostella* gen. nov. Diatom Research 19: 203-228.

Hunt CP, Moskowitz BM, Banerjee SK (1995) Magnetic properties of rocks and minerals. Rock Physics and Phase Relations. A Handbook of Physical Constants: AGU Reference Shelf, 189-204.

Itkonen A and Salonen V-P (1994) The response of sedimentation in three varved lacustrine sequences to air temperature, precipitation and human impact. Journal of Paleolimnology 11: 323-332.

Jacoby GC, D'Arrigo RD, Davaajamts T (1996) Mongolian tree rings and 20th-century warming. Science 273: 771-773.

Juggins S (2003) C^2 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne: 69 pp.

Julius ML (2000) Phylogeny of the cyclostephanoid diatoms: an investigation of their morphology and stratigraphy. Doctoral thesis, University of Michigan, 209 pp.

Kelderman P, Batima P (2006) Water quality assessment of rivers in Mongolia. Water Sci Technol 53: 111-119.

King L, Barker P, Jones RI (2000) Epilithic algal communities and their relationship to environmental variables in lakes of the English Lake District, Freshwater Biology 45: 425-442.

Kolbe RW (1927) Zur Okologie, Morphologie und systematik der brackwasserr-diatomeen. Pflanzenforschung 7: 69-84.

Koninklijk Nederlands Meteorologisch Instituut (KNMI) (2007) Climate Explorer online database:http://climexp.knmi.nl.

Kozhova OM and Zagorenko GF (1976) Winter phytoplankton of Lake Hovsgol in: Sodnom N and Losev NF (eds.) Natural Conditions and Resources of Hovsgol Region, Mongolian and Irkutsk State University, Irkutsk-Ulaanbaatar. (in Russian)

Kozhova OM, Zagorenko GF and Ladeyshchikova Y (1977) Features of Lake Khubsugul phytoplankton in the inter-annual and seasonal aspects. Hydrobiological Journal 13(5): 60-64.

Krammer K and Lange-Bertalot H (1986-1991) Bacillariophyceae. Susswasserflora von Mitteleuropa. Band 2(1-4). Vols. 1-4 Tiel 1(1986, pp. 876) 2(1988, pp. 596) 3(1991, pp. 576) 4(1991, pp.437). Gustav Fischer Verlag, Stuttgart.

Krammer K (2001) Taxonomie und Morphologie von *Brevisira arentii* (Kolbe) Krammer gen. nov., comb. nov. In Jahn, R. et al. [Eds.] Lange-Bertalot-Festschrift: Studies on Diatoms. Ganter Verlag K.G., Ruggell. 9-20.

Lehmkhul F and Lang A (2001) Geomorphological investigations and luminescence dating in the southern part of the Khangay and the Valley of the Gobi Lakes (Central Mongolia). Journal of Quaternary Science 16: 69-87.

Levkov, Z., (submitted): Amphora sensu lato (Amphora sensu stricto & Halamphora) In: Lange-Bertalot,

H. [Ed.] Diatoms of Europe: Diatoms of European Inland Waters and Comparable Habitats Elsewhere. Volume 5. Koeltz, Koenigstein.

Li C, Hao X, Zhao M, Han G, Willms WD (2008) Influence of historic sheep grazing on vegetation and soil properties of a desert steppe in Inner Mongolia. Agriculture, Ecosystems, and Environment 128: 109-116.

Liao N (2002) Deterimination of orthophosphate in waters by flow injection analysis colorimetry (Quikchem Method 10-115-01-1-M). Lachat Instruments, Milwaukee, Wisconsin.

Lotter AF (1998) The recent eutrophication of Baldeggersee (Switzerland) as assessed by fossil diatom assemblages. The Holocene 8: 395–405.

Lydolph P (1977) Climates of the Soviet Union. In: Landsberg HE et al. (eds) World Survey of Climatology, v. 7, Elsevier Scientific Publishing, Amsterdam, 362 pp.

Malmaeus JM, Blenckner T, Markensten H, Persson I (2006) Lake phosphorus dynamics and climate warming: A mechanistic model approach. Ecological Modelling 190: 1-14.

Maroney RL (2005) Conservation of argali *Ovis ammon* in western Mongolia and the Altai-Sayan. Biological Conservation 121: 231-241.

McKnight R (2000) Determination of silica in waters by flow injection analysis (Quikchem Method 10–114–21– 1A). Lachat Instruments, Milwaukee, Wisconsin.

Mearns, R (2004) Sustaining livelihoods on Mongolia's pastoral commons: Insights from a participatory poverty assessment. Development and Change 35(1): 107-139.

Ministry for Nature and the Environment (1996) Biodiversity conservation action plan for Mongolia. Ulaanbaatar, Mongolia.

Ministry for Nature and the Environment (1997) Mongolia Red Book, 2nd Edition. Ulaanbaatar [In Mongolian].

Morales EA and Edlund MB (2003) Studies in selected fragilarioid diatoms (Bacillariophyceae) from Lake Hovsgol, Mongolia. Phycological Research 51: 225-239.

Nagumo T (2003) Taxonomic studies of the subgenus *Amphora* Cleve of the genus *Amphora* (Bacillariophyceae) in Japan. Bibl Diatomol 49.

Nandintsetseg B, Greene JS, Goulden CE (2007) Trends in extreme daily precipitation and temperature near Lake Hövsgöl, Mongolia, International Journal of Climatology 27:341-347.

Niemistö JP, Horppila J (2007) The contribution of ice cover to sediment resuspension in a shallow temperate lake: possible effects of climate change on internal nutrient loading. Journal of Environmental Quality 36: 1318-1323.

Nicholls KH (1998) El Niño, ice cover, and Great Lakes phosphorus: implications for climate warming. Limnology and Oceanography 43: 715-719.

Ohtsuka T and Tuji A (2002) Lectotypification of some pennate diatoms described by Skvortzow in 1936 from Lake Biwa. Phycological Research 50: 243–249.

Oki T and Kanae S (2006) Global hydrological cycles and world water resources. Science 313: 1068-1072.

Olson DM and Dinerstein E (1998) The Global 200: A representation approach to conserving the earth's most biologically valuable ecoregions. Conservation Biology 12: 502-515.

Panagiotopoulous F and Shahgedanova M (2005) Observed trends and teleconnections of the Siberian High: A recently declining center of action. Journal of Climate 18: 1411-1422.

Pappas JL, Stoermer EF (1996) Quantitative method for determining a representative algal sample count. Journal of Phycology 32: 693-696.

Pappas JL and Stoermer EF (2003) Morphometric comparison of the neotype of *Asterionella formosa* Hassall (Heterokontophyta, Bacillariophyceae) with *Asterionella edlundii* from Lake Hovsgol, Mongolia. Diatom. 19: 55-65.

Patrick R, Reimer CW (1966) The diatoms of the United States. Monographic Series of Academy of Natural Sciences of Philadelphia #13. Livingston Publishing Company, Philadelphia.

Peck JA, Khosbayar P, Fowell SJ, Pearce RB, Ariunbileg S, Hansen CS, Sononkhishig S (2002) Mid to Late Holocene climate change in north central Mongolia as recorded in the sediments of Lake Telmen. Palaeogeography, Palaeoclimatology, Palaeoecology 183: 135-153.

Pederson, N et al. (2000) Hydrometeorological Reconstructions for Northeastern Mongolia Derived from Tree Rings: AD 1651-1995, National University of Mongolia, Faculty of Biology; Journal of Biology, no. 11 (164). Dendroclimatic Studies in Mongolia. The MATRIP Project (Special

Issue), Ulaanbaatar.

Popovskaya G (1993) Planktonic diatom algae of Lake Baikal and their long-term monitoring. In: Fifth workshop on diatom algae: Diatom algae as indicators of the changes of climate and environment. Russian Academy of Sciences, Siberian Division, Irkutsk.

Prasad AKSK, Nienow JA, Livingston RJ (1990) The genus *Cyclotella* (Bacillariophyta) in Choctawhatchee Bay, Florida, with special reference to *C. striata* and *C. choctawhatcheeana* sp. nov., Phycologia 29(4):418-436.

Pratt DG, Macmillan DC, Gordon IJ (2004) Local community attitudes to wildlife utilization in the changing economic and social context of Mongolia. Biodiversity and Conservation 13: 591-613.

Quinlan R, Patterson AM, Hall RI, Dillon PS, Wilkinson AN, Cumming BF, Douglas MSV, Smol JP (2003) A landscape approach to examining spatial patterns of limnological variables and long-term environmental chnage in a southern Canadian lake district. Freshwater Biology 48: 1676-1697.

R Development Core Team (2006) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Ramstack JM, Fritz SC, Engstrom DR, Heiskary SA (2003) The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. Journal of Paleolimnology 29:79-94.

Reavie ED and Smol JP (2001) Diatom-environmental relationships in 64 alkaline southeastern Ontario (Canada) lakes: a diatom-based model for water quality reconstructions, Journal of Paleolimnology 25: 25-42.

Renberg I (1990) A procedure for preparing large sets of diatom slides from sediment cores. Journal of Paleolimnology 4: 87-90.

Robbins JA (1978) Geochemical and geophysical applications of radioactive lead. In: Nriagu JO [Ed]. The biogeochemistry of lead in the environment. Elsevier Press. pp 285-293.

Round FE, Crawford RM, Mann DG (1990) The diatoms: biology and morphology of the genera, Cambridge University Press, Cambridge. 747pp.

Ryves DB, Battarbee RW, Juggins S, Fritz SC, Anderson NJ (2006) Physical and chemical predictors of diatom dissolution in freshwater and saline lake sediments in North America and West Greenland. Limnology and Oceanography 51(3): 1355-1368.

Sayer CD (2001) Problems with the application of diatom-total phosphorus transfer functions: examples from a shallow English lake. Freshwater Biology 46: 743-757.

Schindler DW and Donahue WF (2006) An impending water crisis in Canada’s western prairie provinces. Proceedings of the National Academy of Sciences 103 (19): 7210-7216.

Shinneman ALC, Edlund MB, Almendinger JE, Soninkhishig N (in press) Diatoms as indicators of water quality in Western Mongolian lakes: a 54-site calibration set. Journal of Paleolimnology.

Shinoda M and Morinaga Y (2005) Developing a combined drought-dzud early warning system in Mongolia. Geographical Review of Japan 78 (13): 928-950. In Japanese with English abstract.

Siurua H and Swift J (2002) Drought and *zud* but no famine (yet) in the Mongolian herding economy. Institute of Development Studies Bulletin 33 (4): 88-97.

Skabitschevsky AP (1967) De specie nova e genere *Cyclotella* Kütz. (Bacillariophyta). *Novitates Systematicae Plantarum non Vascularum* 1967: 52-53.

Skvortzow BW (1937) Bottom diatoms from Olhon Gate of Baikal Lake, Siberia. Philippine Journal of Science 62: 293-377.

Skvortzow BW and Meyer CI (1928) A contribution to the diatoms of Baikal Lake. Proceedings of the Sungaree River Biological Station 1(5): 1-55.

Slaydon C, Traynor JJ (2000) Lakes during the evolution of Mongolia. In: Gierlowski-Kordesch EH and Kelts KR (eds), Lake basins through space and time: AAPG Studies in Geology 46: 35-57.

Smol JP, Wolfe AP, Birks HJB, Douglas MSV, Jones VJ, Korhols A, Pienitz R, Rühland K, Sorvari S, Antoniades D, Brooks SJ, Fallu M-A, Hughes M, Keatley BE, Laing TE, Michelutti N, Nazarova L, Nyman M, Paterson AM, Perren B, Quinlan R, Rautio M, Saulnier-Talbot E, Siitonen S, Solovieva N, Weckström J (2005) Climate-driven regime shifts in the biological communities of arctic lakes. Proceedings of the National Academy of Sciences (PNAS) 102: 4397-4402.

Sneath D (1999) Mobility, technology, and decollectivization of pastoralism in Mongolia. Kotkin S, Elleman BA (eds). Mongolia in the Twentieth Century: Landlocked Cosmopolitan. Armonk (NY): M.E. Sharpe Publishing: p223-236.

Solomon S, Qin D, Manning M, Marquis M, Averyt K, Tignor MMB, Miller HL, Chen A(eds) (2007) Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge.

Soninkhishig N (1998) Diatoms of the Tuul River. Master‘s thesis, National University of Mongolia, Botany Department, 29 pp. [in Mongolian].

Soninkhishig N, Edlund MB, Peck JA (2001) Diatom-based paleoenvironmental reconstruction of Lake Telmen for the last 6230 years. Mongolian Journal of Biological Sciences 1(1): 55-68 .

Sternberg T (2008) Environmental challenges in Mongolia’s dryland pastoral landscape, Journal of Arid Environments 72:1294-1304.

Stoermer EF, Smol JP (eds) (1999) The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, 482 pp.

Stubblefield A, Chandra S, Eagan S, Tuvshinjargal D, Davaadorzh G, Gilroy D, Sampson J, Thorne J, Allen B, Hogan Z (2005) Impacts of gold mining and land use alterations on the water quality of Central Mongolian rivers. Integrated Environmental Assessment and Management 1(4): 365-373.

Stuiver M and Reimer PJ (1993) Extended 14C database and revised CALIB radiocarbon calibration program. Radiocarbon 35: 215-230.

Stuiver M, Reimer PJ and Reimer R (1999) CALIB radiocarbon Calibration (HTML Version 4.2). http:\\depts.washington.edu\qil\calib\.

Tanaka H (2007) Taxonomic studies of the genera *Cyclotella* (Kützing) Brébisson, *Discostella* Houk et Klee and *Puncticulata* Håkansson in the family *Stephanodiscaceae* Glezer et Makarova (Bacillariophyta) in Japan. Bibliotheca Diatomologica 53: 1-205.

Tarasov, P, et al. (1996) Lake status records from the former Soviet Union and Mongolia: documentation of the second version of the database, NOAA Paleoclimatology Publications Series Report No. 5, Boulder: 224 pp.

Tarasov P, Dorofeyuk N, Metel’Tseva E (2000) Holocene vegetation and climate changes in Hoton-Nur basin, northwest Mongolia, Boreas, 29: 117-126.

ter Braak CJF (1986) Canonical correspondence analysis: A new eigenvector technique for multi-variate direct gradient analysis. Ecology 67: 1167-1179.

Theriot EC, Håkansson H, Kociolek JP, Round FE, Stoermer EF (1987) Validation of the centric diatom genus *Cyclostephanos*. British Phycological Journal 22: 345-347.

Triplett L (2002) Standard Operating Procedures for Grain Size Analysis Sample Preparation. Limnological Research Center, http://lrc.geo.umn.edu/gz.pdf

Tuji A and Houki A (2001) Centric diatoms in Lake Biwa. Lake Biwa Study Monographs, Number 7. Lake Biwa Research Institute, Otsu, Japan, 90 pp.

Umbanhowar CE, Shinneman ALC, Tserenkhand G, Johnson L, Lor P, Nail K (in press) Regional fire history of western Mongolia since cal yr AD 800, based on charcoal analysis of sediments of nine lakes. The Holocene.

van Geel B, Bokovenko NA, Burova, ND, Chugunov KV, Dergachev VA, Dirksen VG, Kulkova M, Nagler A, Parzinger H, van der Plicht J, Vasiliev SS, Zaitseva GI (2004) Climate change and the expansion of the Sythian culture after 850 BC: a hypothesis. Journal of Archological Science 31: 1735-1742.

Weatherford J (2004) Genghis Khan and the making of the modern world, Three Rivers Press, New York, NY: 271 pp.

Westover K, Fritz SC, Blyakharchuk T, Wright HE (2006) Diatom paleolimnological record of Holocene climatic and environmental change in the Altai Mountains, Siberia. Journal of Paleolimnology 35: 519-541.

Wetzel RG (2001) Limnology: lake and river ecosystems. San Diego (CA): Elsevier Academic Press. 1006pp.

Williams RM, Edlund MB, Stoermer EF (1999) Taxonomy and morphology of *Cymbella stuxbergii* from lakes in the Baikal Rift Zone. Diatom Research 14:381-392.

Williams WD (2002) Environmental threats to salt lakes and the likely status of inland saline ecosystems in 2025. Environmental Conservation 29 (2): 154-167.

World Bank (2003) From goats to coats: institutional reform in Mongolia's cashmere sector, Poverty Reduction and Economic Management Unit East Asia and Pacific Region. Report No. 26240-MOG, 110 pp.

World Bank (2006) Mongolia poverty assessment, poverty reduction and economic management. East Asia and the Pacific Region Report No. 35660-MN, 105 pp.

Wright HE, Jr. (1990) An improved Hongve sampler for surface sediments. Journal of Paleolimnology 4: 91-92.

Wünnemann B, Mischke S, Chen F (2006) A Holocene sedimentary record from Bosten Lake, China. Palaeogeography, Palaeoclimatology, Palaeoecology 234: 223-238.

Wunsam S, Schmidt R, Klee, R (1995) *Cyclotella*-taxa (Bacillariophyceae) in lakes of the Alpine region and their relationship to environmental variables. Aquatic Sciences 57: 360-386.

Yang B, Braeuning A, Johnson KR, Yafeng S (2001) General characteristics of temperature variation in China during the last two millennia. Geophysical Research Letters 29(9).

Yang B, Wang J, Brauning A, Dong Z, Esper, J (2008) Late Holocene climatic and environmental changes in arid central Asia. Quaternary International.

Yatagai A and Yasunari T (1994) Trends and decadal-scale fluctuations of surface air temperature and precipitation over China and Mongolia during the recent 40 year period (1951-1990). Journal of the Meteorological Society of Japan 72 (6): 937-957.

Zhane Y, Kong Z-C, Ni J, Yan S, Yang Z-J (2007) Late Holocene palaeoenvironmental change in central Tianshan of Xinjiang, northwest China. Grana 46(3): 197-213.

Site Code	Site Number	Temperature (°C)	Specific conductivity (µS cm^{-1})	pH	DO (mg L^{-1})	Secchi depth (m)	Chlorophyll-a (relative to standard)	Total phosphorus (mg L^{-1})	Total nitrogen (mg L^{-1})
ACHITN	16	20.6	328	8.96	9.2	0.95	77	0.026	1.709
AIRIGN	53	20.5	4350	9.17	9.5	2.75	56	0.024	1.091
ALALTN	27	13.1	225	9.07	9.5	0.52	245	0.123	0.983
ALKHAR	26	11.6	41	8.20	8.4	3.70	23	0.015	0.319
ARALNR	38	10.2	489	9.08	11.4	0.45	150	0.122	1.529
BAGANR	15	20.4	7050	9.52	11.3	0.20	1426	0.461	5.827
BARSAL	9	13.6	357	9.66	8.8	0.70	184	0.058	2.872
BAYANR	71	22.6	465	8.53	8.3	3.65	37	0.007	0.499
BELTLK	93	16.0	3252	9.32	10.1	2.00	162	0.028	2.770
BUYANT	10	14.9	319	8.78	8.5	3.40	26	0.014	0.869
DALAIN	47	17.7	161	8.90	9.1	1.25	50	0.022	0.601
DBAYAN	106	19.1	370	8.88	8.8	6.60	19	0.011	0.410
DEVPD1	109	25.7	42900	8.89	9.5	0.04	8121	2.635	12.114
DNBAGA	72	22.7	977	8.57	6.6	0.80	238	0.068	1.755
DOROON	29	12.5	4543	8.81	9.1	0.40	742	0.159	2.626
GASHUN	104	14.5	3300	9.38	11.8	0.35	117	0.115	3.809
JJDORO	28	10.4	7500	8.76	9.0	0.18	1533	0.328	4.624
JJTOLB	25	12.7	216	9.50	9.2	0.75	134	0.069	1.063
KHAGNR	39	12.4	282	8.21	9.8	1.65	40	0.045	1.509
KHARNR	49	20.0	262	8.77	9.6	1.10	59	0.027	1.318
KHOLB2	83	17.0	2772	9.34	8.3	0.85	96	0.052	2.689
KHOLB3	107	18.0	296	9.63	12.4	0.85	60	0.058	1.139
KHOLBO	6	14.4	69	7.54	6.7	0.53	682	0.145	1.515
KHRUSN	46	19.1	120	8.33	8.6	0.95	36	0.023	0.262
KHRUSS	43	18.1	197	9.45	9.8	0.35	131	0.071	1.928
KHUNT2	105	23.1	250	9.62	17.5	1.74	41	0.030	1.069
KHUNTN	85	16.9	2958	9.33	7.8	1.00	133	0.042	2.893
KHYAR2	123	19.7	9450	9.30	9.7	5.50	9	0.020	0.962
KHYAR3	127	18.9	9400	9.31	10.1	5.50	5	0.031	1.147
KHYARG	54	19.9	8610	9.12	9.5	6.80	9	0.027	1.084
OIGONR	82	19.3	32276	9.26	7.7	2.15	64	0.058	4.849
OLGOIN	116	16.9	8550	9.32	10.6	0.40	1978	0.296	4.581
OLONN2	7	14.9	78	8.46	8.1	0.90	48	0.035	0.544
SHUVUU	55	24.0	10300	9.07	9.5	0.76	165	0.148	2.838
TAKILT	99	16.2	3370	9.28	8.6	1.65	57	0.041	2.085
TELMEN	95	16.2	8630	9.35	9.5	3.10	28	0.017	1.505
TOLBON	24	16.3	951	9.16	10.5	2.00	24	0.020	0.938
TSAGN1	112	19.9	29083	9.52	11.0	1.45	25	0.037	4.268
TSAGN2	117	17.3	12830	8.87	9.8	0.75	104	0.104	2.780
TSEGEN	100	16.0	12430	9.14	11.8	0.45	201	0.196	3.688
TSETNR	91	13.9	771	8.91	7.6	0.60	456	0.151	3.250
TSGNPL	102	17.0	25500	9.10	9.5	0.07	3821	1.363	12.435
TSVPD1	78	22.0	1040	8.55	9.5	0.11	1967	0.763	1.848
TSVPD2	79	16.0	1740	9.50	9.5	0.15	672	0.492	3.755
TSVPD3	80	18.1	15325	9.43	8.6	1.20	50	0.082	3.137
ULAANR	84	16.0	1990	9.30	9.5	0.27	788	0.180	4.647
UVBAGA	61	23.4	26391	9.86	9.0	1.75	84	0.105	2.726
UVSNRE	63	23.2	20363	9.43	7.7	1.90	45	0.023	1.173
UVSNRS	62	23.2	20682	9.44	8.6	3.00	28	0.016	1.155
XOXNR1	32	18.3	2200	9.53	9.5	1.32	70	0.056	0.607
XOXNR2	33	15.0	3000	8.70	9.5	0.51	298	0.113	1.480
XOXNR3	34	15.0	7900	9.06	9.5	0.15	889	0.194	4.357
XOXNR4	35	19.2	1530	9.32	9.5	0.67	198	0.071	1.043
YALAAT	96	17.0	220	9.61	9.5	1.48	60	0.036	0.887
ZAGASN	37	12.3	473	8.64	10.1	0.80	217	0.062	0.931
ZOSTNR	52	19.0	404	9.63	9.5	0.15	391	0.340	4.103
ZUUNKH	17	20.2	383	8.73	8.8	0.65	152	0.040	1.621

Appendix 1-1: Physical and chemical data for the original 57 lakes used in developing the calibration set. Site Numbers are as in Figure 1-1. Lake types (see Chapter 1) are abbreviated as LS (large and shallow), SS (small and shallow), LD (large and deep), LS (large and shallow), and TVL (terminal valley lake).

Site Code	Site Number	NO_3 as N (mg L^{-1})	Kjeldahl nitrogen (mg L^{-1})	NH_4 as N (mg L^{-1})	Organic N (mg L^{-1})	Cl (mg L^{-1})	SO_4 (mg L^{-1})	Na (mg L^{-1})	Al (mg L^{-1})
ACHITN	16	0.004	1.705	0.089	1.616	13.87	25.36	31.36	0.007
AIRIGN	53	0.000	1.091	0.040	1.050	623.72	968.06	1130.00	0.009
ALALTN	27	0.049	0.934	0.017	0.917	8.22	18.00	22.56	0.005
ALKHAR	26	0.000	0.319	0.020	0.299	1.12	2.41	2.16	0.004
ARALNR	38	0.000	1.529	0.033	1.496	53.04	57.27	43.44	0.012
BAGANR	15	0.016	5.810	0.135	5.676	1541.72	542.18	1613.00	0.040
BARSAL	9	0.000	2.872	0.160	2.712	20.51	13.75	14.55	0.003
BAYANR	71	0.110	0.389	0.124	0.264	8.63	55.55	32.24	0.025
BELTLK	93	0.000	2.770	0.187	2.583	596.35	63.85	570.40	0.017
BUYANT	10	0.000	0.869	0.036	0.833	11.20	11.15	12.01	0.004
DALAIN	47	0.000	0.601	0.048	0.553	3.91	9.87	9.48	0.005
DBAYAN	106	0.004	0.406	0.044	0.362	9.95	22.69	27.06	0.020
DEVPD1	109	0.022	12.091	2.423	9.669	11222.66	7029.52	10160.00	0.138
DNBAGA	72	0.006	1.748	0.160	1.589	32.82	228.29	102.80	0.006
DOROON	29	0.000	2.626	0.049	2.577	1353.94	288.30	935.30	0.041
GASHUN	104	0.011	3.798	0.167	3.631	294.87	623.69	530.70	0.027
JJDORO	28	0.005	4.619	0.086	4.533	2298.87	502.50	1532.00	0.059
JJTOLB	25	0.000	1.063	0.022	1.041	16.35	12.53	18.48	0.013
KHAGNR	39	0.004	1.505	0.616	0.889	18.74	9.12	12.90	0.021
KHARNR	49	0.000	1.318	0.028	1.290	10.38	17.33	22.99	0.003
KHOLB2	83	0.005	2.684	0.253	2.430	430.32	193.15	491.00	0.020
KHOLB3	107	0.004	1.135	0.052	1.083	9.03	9.70	19.94	0.018
KHOLBO	6	0.000	1.515	0.055	1.459	1.94	2.68	3.03	0.076
KHRUSN	46	0.000	0.262	0.003	0.258	2.09	6.07	5.17	0.032
KHRUSS	43	0.006	1.922	0.022	1.900	8.37	15.53	20.97	0.059
KHUNT2	105	0.570	0.499	0.127	0.373	6.24	12.76	15.97	0.008
KHUNTN	85	0.006	2.887	0.260	2.627	457.14	199.89	519.40	0.010
KHYAR2	123	0.005	0.957	0.084	0.873	1283.50	2082.54	1960.00	0.072
KHYAR3	127	0.000	1.147	0.083	1.063	1285.27	2089.82	1969.00	0.092
KHYARG	54	0.000	1.084	0.033	1.051	1312.27	2100.44	2180.87	0.000
OIGONR	82	0.000	4.849	0.357	4.492	7132.29	7433.24	7977.00	0.009
OLGOIN	116	0.013	4.567	0.189	4.379	1559.50	1509.64	1828.00	0.056
OLONN2	7	0.000	0.544	0.019	0.524	0.95	2.44	1.92	0.013
SHUVUU	55	0.014	2.824	0.066	2.759	8971.16	12093.12	12821.26	0.032
TAKILT	99	0.000	2.085	0.137	1.948	547.24	509.76	521.70	0.043
TELMEN	95	0.000	1.505	0.090	1.415	1414.33	1699.56	1599.00	0.010
TOLBON	24	0.000	0.938	0.027	0.911	53.74	51.10	113.10	0.006
TSAGN1	112	0.000	4.268	0.313	3.954	4671.76	8668.66	7143.00	0.327
TSAGN2	117	0.004	2.776	0.147	2.629	2297.69	4182.29	2579.00	0.079
TSEGEN	100	0.004	3.684	0.200	3.484	2915.11	2098.27	2512.00	0.043
TSETNR	91	0.005	3.245	0.252	2.993	78.76	57.18	113.70	0.016
TSGNPL	102	0.013	12.422	0.650	11.772	6023.79	4083.14	4625.00	0.218
TSVPD1	78	0.006	1.842	0.179	1.663	186.36	275.25	176.30	0.009
TSVPD2	79	0.008	3.747	0.170	3.576	231.84	349.86	259.40	0.120
TSVPD3	80	0.006	3.131	0.355	2.776	2466.36	3930.16	3544.00	0.027
ULAANR	84	0.014	4.634	0.373	4.261	276.65	170.59	321.50	0.118
UVBAGA	61	0.014	2.712	0.239	2.474	2842.05	9332.22	6679.50	0.028
UVSNRE	63	0.005	1.168	0.145	1.023	4750.46	3667.45	4014.00	0.043
UVSNRS	62	0.004	1.151	0.136	1.015	4817.02	3703.24	4014.00	0.979
XOXNR1	32	0.000	0.607	0.020	0.587	550.38	354.74	428.10	0.054
XOXNR2	33	0.006	1.474	0.014	1.460	670.06	453.42	520.90	0.017
XOXNR3	34	0.009	4.348	0.042	4.306	1911.80	1313.53	1516.00	0.030
XOXNR4	35	0.000	1.043	0.021	1.022	266.39	256.01	250.50	0.018
YALAAT	96	0.005	0.881	0.061	0.820	4.69	23.61	19.21	0.010
ZAGASN	37	0.000	0.931	0.023	0.908	47.30	53.46	37.61	0.004
ZOSTNR	52	0.006	4.097	0.071	4.026	31.07	22.47	58.37	0.169
ZUUNKH	17	0.000	1.621	0.077	1.544	14.91	28.59	33.26	0.002

Site Code	Site Number	Si (mg L^{-1})	K (mg L^{-1})	Ca (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})	Dissolved organic carbon (mg L^{-1})	Dissolved inorganic carbon (mg L^{-1})	H_2CO_3 (mg L^{-1})
ACHITN	16	2.02	6.71	18.75	0.0000	0.0005	15.45	31.39	0.37
AIRIGN	53	9.36	120.50	13.73	0.1360	0.0042	13.95	298.44	1.73
ALALTN	27	7.44	1.10	26.53	0.0000	0.0023	2.61	23.83	0.25
ALKHAR	26	0.10	0.32	5.92	0.0279	0.0007	3.47	4.41	0.38
ARALNR	38	9.53	2.63	41.91	0.0000	0.0018	9.99	36.02	0.39
BAGANR	15	13.11	137.70	11.40	0.0000	0.0022	16.45	257.19	0.53
BARSAL	9	10.95	8.31	35.25	0.0000	0.0019	40.71	34.64	0.08
BAYANR	71	2.67	4.43	26.78	0.0686	0.0004	3.57	45.17	1.42
BELTLK	93	11.75	68.47	10.92	0.6080	0.0043	45.82	191.57	0.86
BUYANT	10	1.43	4.86	38.32	0.0000	0.0003	45.08	35.21	0.71
DALAIN	47	1.43	2.20	18.47	0.0000	0.0003	5.81	17.53	0.26
DBAYAN	106	2.45	7.70	24.68	0.0326	0.0007	4.56	44.34	0.65
DEVPD1	109	93.95	610.35	37.74	6.8400	0.0372	0.39	614.04	4.80
DNBAGA	72	6.17	9.68	40.05	0.1230	0.0003	9.02	59.73	1.63
DOROON	29	9.13	39.20	69.71	0.0000	0.0005	18.38	65.12	1.09
GASHUN	104	20.72	61.62	5.95	0.2100	0.0016	24.25	175.89	0.69
JJDORO	28	11.87	63.15	82.66	0.0000	0.0038	27.65	54.77	1.02
JJTOLB	25	2.14	1.31	17.52	0.0000	0.0038	8.08	17.24	0.06
KHAGNR	39	0.55	2.50	38.53	0.0000	0.0763	9.55	29.81	2.39
KHARNR	49	2.30	4.89	19.83	0.0000	0.0007	12.90	28.03	0.53
KHOLB2	83	15.27	28.66	18.29	1.6100	0.0041	35.65	151.76	0.64
KHOLB3	107	6.18	6.77	12.06	0.0323	0.0019	6.80	22.97	0.05
KHOLBO	6	2.34	0.90	9.42	0.6770	0.2460	9.96	8.48	3.01
KHRUSN	46	1.54	1.24	16.52	0.0023	0.0008	2.35	14.19	0.78
KHRUSS	43	2.23	5.20	11.46	0.0477	0.0049	15.72	18.94	0.07
KHUNT2	105	4.05	4.01	26.08	0.1090	0.0023	3.60	28.42	0.06
KHUNTN	85	15.72	30.97	15.22	2.1000	0.0000	4.43	154.77	0.67
KHYAR2	123	46.96	228.20	10.32	0.6330	0.0000	20.78	367.55	1.36
KHYAR3	127	40.64	230.40	9.95	0.7670	0.0000	19.88	366.24	1.34
KHYARG	54	16.76	260.26	10.97	0.1330	0.0004	19.53	486.83	2.97
OIGONR	82	171.80	117.45	26.06	11.8000	0.0000	67.58	289.90	0.94
OLGOIN	116	59.22	50.59	20.48	6.6900	0.0000	28.37	215.22	0.82
OLONN2	7	1.06	0.79	12.36	0.0380	0.0007	5.88	8.84	0.39
SHUVUU	55	26.12	1401.61	11.72	0.0771	0.0080	17.00	1377.78	8.67
TAKILT	99	12.22	11.12	25.33	1.2400	0.0030	25.34	108.33	0.53
TELMEN	95	36.85	61.41	13.38	3.6400	0.0000	19.84	272.61	0.96
TOLBON	24	0.62	14.87	13.20	0.0000	0.0003	10.71	109.16	0.81
TSAGN1	112	146.50	125.20	30.81	16.3000	0.0000	42.63	173.84	0.26
TSAGN2	117	127.50	117.40	86.06	12.9000	0.0000	26.59	112.71	1.30
TSEGEN	100	34.08	137.70	33.58	0.6820	0.0029	38.34	155.68	0.92
TSETNR	91	10.21	10.21	11.86	0.0989	0.0017	25.75	55.90	0.82
TSGNPL	102	125.30	225.60	77.14	15.4000	0.2180	3.42	202.47	1.16
TSVPD1	78	9.61	16.21	123.60	0.4530	0.0168	18.19	48.49	1.41
TSVPD2	79	12.55	5.53	45.25	0.7110	0.0033	12.11	42.08	0.12
TSVPD3	80	99.79	37.70	7.81	5.1600	0.0000	6.39	346.81	0.83
ULAANR	84	27.63	19.83	23.26	2.1200	0.0160	12.56	97.20	0.48
UVBAGA	61	101.16	84.10	3.80	9.6100	0.0021	6.14	447.43	0.19
UVSNRE	63	32.75	183.30	14.78	1.1800	0.0000	17.73	442.70	0.88
UVSNRS	62	42.65	184.30	15.65	1.1300	0.0007	17.27	235.62	0.45
XOXNR1	32	4.34	1.89	37.95	0.0000	0.0004	4.87	55.29	0.14
XOXNR2	33	5.95	7.85	51.55	0.0000	0.0062	7.90	92.16	1.97
XOXNR3	34	2.08	21.15	22.50	0.0000	0.0033	33.50	166.67	1.33
XOXNR4	35	7.02	3.57	41.56	0.0000	0.0026	9.21	61.58	0.28
YALAAT	96	7.52	0.73	20.13	0.0962	0.0009	6.95	25.34	0.06
ZAGASN	37	7.85	2.81	45.30	0.0000	0.0010	7.42	36.97	1.08
ZOSTNR	52	6.73	6.91	14.87	0.0913	0.0059	21.49	32.09	0.07
ZUUNKH	17	4.83	7.04	25.96	0.0000	0.0007	17.51	37.45	0.77

Site Code	Site Number	HCO_3 (mg L^{-1})	CO_3 (mg L^{-1})	Site Latitude (dec. degree)	Site Longitude (dec. degree)	Site elevation (m)	Lake Type
ACHITN	16	151.19	7.82	49.45	90.65	1438	LS
AIRIGN	53	1314.09	197.21	48.91	93.37	1030	TVL
ALALTN	27	114.65	6.05	48.36	90.40	2211	SS
ALKHAR	26	21.87	0.13	48.38	90.05	2510	SD
ARALNR	38	172.87	9.58	48.50	90.62	2375	LS
BAGANR	15	931.75	368.28	49.51	90.80	1547	SS
BARSAL	9	143.65	31.72	49.63	91.11	2530	SS
BAYANR	71	223.00	4.73	50.01	94.01	981	LD
BELTLK	93	827.00	143.00	49.15	97.42	2040	LD
BUYANT	10	172.96	5.13	49.62	91.12	2553	SD
DALAIN	47	85.47	3.31	48.32	92.70	1156	LS
DBAYAN	106	215.00	9.11	48.46	95.16	1481	LD
DEVPD1	109	2560.00	543.00	48.69	95.35	1540	SS
DNBAGA	72	294.00	7.87	49.92	93.85	981	SD
DOROON	29	312.51	17.00	48.24	90.66	2394	LD
GASHUN	104	747.00	144.00	48.48	95.34	1520	SS
JJDORO	28	262.70	14.31	48.24	90.68	2394	SS
JJTOLB	25	76.63	10.71	48.44	90.20	2089	SS
KHAGNR	39	148.02	1.09	48.56	90.60	2426	LS
KHARNR	49	137.41	4.39	48.19	93.24	1132	LS
KHOLB2	83	653.00	116.00	49.02	97.14	1940	LD
KHOLB3	107	95.00	21.30	48.57	95.42	1560	SS
KHOLBO	6	40.08	0.06	49.70	91.09	2570	SS
KHRUSN	46	70.56	0.74	48.34	92.23	1157	TVL
KHRUSS	43	84.08	11.89	47.94	91.99	1157	TVL
KHUNT2	105	116.00	27.90	48.46	95.27	1505	SS
KHUNTN	85	666.00	117.00	49.05	97.16	1939	LD
KHYAR2	123	1470.00	385.00	49.19	93.63	1028	TVL
KHYAR3	127	1470.00	384.00	49.31	92.85	1028	TVL
KHYARG	54	2111.52	353.10	49.08	93.32	1028	TVL
OIGONR	82	1050.00	411.00	49.21	96.62	1680	LD
OLGOIN	116	874.00	215.00	48.92	94.93	1382	SS
OLONN2	7	43.98	0.54	49.71	91.07	2568	SS
SHUVUU	55	5937.61	1036.60	48.97	93.32	1019	SS
TAKILT	99	473.00	76.10	48.81	96.81	1841	LD
TELMEN	95	1090.00	285.00	48.87	97.30	1789	LD
TOLBON	24	508.01	45.03	48.58	90.01	2079	LD
TSAGN1	112	522.00	355.00	48.94	95.28	1458	SS
TSAGN2	117	517.00	53.30	48.91	94.87	1370	LD
TSEGEN	100	666.00	122.00	48.71	95.86	1882	LD
TSETNR	91	271.00	12.10	49.10	97.18	1933	SS
TSGNPL	102	834.00	191.00	48.72	95.85	1882	SS
TSVPD1	78	239.00	6.06	49.25	95.64	1635	SS
TSVPD2	79	174.00	38.60	49.24	95.66	1622	SS
TSVPD3	80	1240.00	511.00	49.24	95.67	1650	SS
ULAANR	84	430.00	62.10	49.09	97.18	1935	SS
UVBAGA	61	882.00	1370.00	50.02	92.89	759	SS
UVSNRE	63	1470.00	762.00	50.25	93.26	759	TVL
UVSNRS	62	776.00	414.00	50.08	92.83	759	TVL
XOXNR1	32	220.90	58.90	48.30	90.43	2232	SS
XOXNR2	33	448.24	17.78	48.30	90.43	2228	SS
XOXNR3	34	749.96	93.96	48.30	90.42	2225	SS
XOXNR4	35	270.50	41.38	48.31	90.42	2223	SS
YALAAT	96	107.00	21.50	48.86	96.94	1824	SS
ZAGASN	37	182.83	3.89	48.51	90.61	2376	SD
ZOSTNR	52	131.01	31.46	48.89	93.31	1032	LS
ZUUNKH	17	183.74	5.67	49.39	90.63	1437	LS

Appendix 1-2: Distribution and calculated optima and tolerances for all species used in the calibration set (Chapter 1). All total phosphorus (TP) measurements are in (log) mg L^{-1}. All specific conductivity (SC) measurements are in (log) µS cm^{-1}.

Genus	**species**	**variety**	**form**	**authority**	**# lakes**	**Max**	**log TP Opt.**	**log TP Tol.**	**log TP Opt. (boot)**	**log TP Tol. (boot)**	**log SC Opt.**	**log SC Tol.**	**log SC Opt. (boot)**	**log SC Tol. (boot)**
Achnanthes	*bahusiensis*			(Grunow) Lange-Bert.	3	1.25	-1.44	0.22	-1.45	0.22	4.31	0.26	4.29	0.27
Achnanthes	*minuscula*			Hust.	2	1.25	-1.75	0.14	-1.74	0.24	1.83	0.32	1.84	0.34
Achnanthidium	*exiguum*			(Grunow) Czarn.	5	0.75	-1.62	0.36	-1.63	0.30	2.49	0.54	2.44	0.44
Achnanthidium	*minutissimum*			(Kütz.) Czarn.	26	7.5	-1.28	0.34	-1.28	0.33	2.68	0.47	2.70	0.46
Amphora	*coffeaeformis*			(C.Agardh) Kütz.	14	12.75	-0.76	0.78	-0.84	0.62	4.22	0.24	4.21	0.22
Amphora	*commutata*			Grunow	7	0.75	-1.30	0.42	-1.29	0.37	3.89	0.33	3.89	0.30
Amphora	*aequalis*			Krammer	2	6	-1.44	0.82	-1.21	0.48	4.23	0.31	4.15	0.33
Amphora	*inariensis*			Krammer	20	24.25	-1.11	0.36	-1.14	0.35	3.27	0.55	3.23	0.53
Amphora	*libyca*			Ehrenb.	32	13	-1.06	0.45	-1.07	0.43	3.23	0.62	3.24	0.59
Amphora	*ovalis*			(Kütz.) Kütz.	7	2.25	-1.16	0.52	-1.15	0.43	2.86	0.51	2.90	0.48
Amphora	*perpusilla*			(Grunow) Grunow in VanHeurck	31	46.5	-1.27	0.41	-1.28	0.39	3.21	0.64	3.18	0.61
Amphora	*veneta*			Kütz.	5	1.5	-0.62	0.37	-0.66	0.34	2.98	0.67	3.06	0.57
Amphora	*thumensis*			(Mayer) A.Cleve	7	3.5	-1.80	0.33	-1.76	0.27	2.53	0.34	2.51	0.29
Amphora	*mong. 1*				3	1.5	-0.62	1.11	-0.80	0.64	4.24	0.27	4.23	0.26
Amphora	*mong. 2*				3	13.25	-1.37	0.26	-1.42	0.22	4.42	0.20	4.36	0.24
Amphora	*veneta*	*capitata*		E.Y.Haw.	7	1.25	-1.18	0.36	-1.20	0.31	4.13	0.55	4.11	0.51
Anomoeoneis	*sphaerophora*			(Ehrenb.) Pfitz.	8	5	-1.08	0.23	-1.09	0.21	4.09	0.52	4.04	0.46
Anomoeoneis	*sphaerophora*		*costata*	(Kütz.) A.M.Schmid	10	11.5	-0.99	0.46	-1.01	0.44	4.33	0.32	4.25	0.27
Asterionella	*formosa*			Hass.	2	9.25	-1.17	0.21	-1.11	0.26	2.68	0.01	2.68	0.22
Brachysira	*vitrea*			(Grunow) R.Ross in B.Hartley	3	2	-1.50	0.27	-1.57	0.28	2.54	0.12	2.54	0.18

Genus	species	variety	form	authority	# lakes	Max	log TP Opt.	log TP Tol.	log TP Opt. (boot)	log TP Tol. (boot)	log SC Opt.	log SC Tol.	log SC Opt. (boot)	log SC Tol. (boot)
Brachysira	*aponina*			Kütz.	2	9.75	-1.39	0.32	-1.29	0.29	4.43	0.25	4.35	0.30
Brachysira	*liliana*			Lange-Bert.	3	2	-1.38	0.14	-1.39	0.19	3.12	1.16	3.15	0.74
Caloneis	*bacillum*			(Grunow) Cleve	5	0.75	-1.24	0.38	-1.20	0.31	2.44	0.65	2.51	0.49
Caloneis	*schumanniana*	*lancettula*		Hust.	2	1	-0.59	0.17	-0.59	0.25	3.25	0.91	3.26	0.58
Caloneis	*schumanniana*			(Grunow) Cleve	6	0.75	-1.30	0.32	-1.30	0.26	3.06	0.45	3.06	0.40
Chaetoceros	*mong. 1*				5	3	-1.14	0.63	-1.02	0.52	3.84	0.37	3.85	0.34
Chaetoceros	*mong. 2*				2	3.5	-1.22	0.43	-1.31	0.35	4.14	0.15	4.11	0.27
Cocconeis	*neothumensis*			Krammer	17	6.5	-1.43	0.32	-1.43	0.30	3.66	0.71	3.64	0.67
Cocconeis	*pediculus*			Ehrenb.	3	9.25	-1.35	0.21	-1.24	0.29	4.47	0.12	4.40	0.23
Cocconeis	*placentula*	*euglypta*		(Ehrenb.) Grunow	20	8.5	-1.12	0.38	-1.11	0.37	3.51	0.75	3.52	0.71
Cocconeis	*placentula*	*lineata*		(Ehrenb.) VanHeurck	27	14.25	-1.18	0.45	-1.19	0.43	3.28	0.78	3.28	0.74
Cocconeis	*placentula*	*baicalensis*		Skvortzow	3	25.25	-0.92	0.22	-1.02	0.18	2.36	0.17	2.45	0.18
Craticula	*ambigua*			(Ehrenb.) D.G.Mann in Round, Crawford & Mann	2	1	-0.93	0.37	-1.02	0.32	2.80	0.31	2.72	0.34
Craticula	*halophila*			(Grunow) D.G. Mann in Round, Crawford & Mann	4	1.75	-1.38	0.31	-1.38	0.31	3.52	0.30	3.59	0.27
Ctenophora	*pulchella*			(Ralfs ex Kütz.) D.M.Williams & Round	10	1.75	-1.04	0.58	-1.02	0.53	3.61	0.67	3.61	0.61
Cyclotella	*choctawatcheeana*			Prasad	2	19.5	-1.65	0.10	-1.68	0.22	4.31	0.00	4.31	0.22
Cyclotella	*ocellata*			Pant.	5	37	-2.02	0.39	-1.86	0.24	2.64	0.14	2.60	0.13
Cyclotella	*radiosa*			Grunow	27	53	-1.37	0.39	-1.36	0.37	3.36	0.54	3.34	0.51
Cyclotella	*mong. 1*				3	30.75	-1.86	0.11	-1.85	0.18	2.51	0.05	2.51	0.15

Genus	species	variety	form	authority	# lakes	Max	log TP Opt.	log TP Tol.	log TP Opt. (boot)	log TP Tol. (boot)	log SC Opt.	log SC Tol.	log SC Opt. (boot)	log SC Tol. (boot)
Cyclotella	*mong. 2*				2	15.75	-1.22	0.37	-1.09	0.30	4.49	0.43	4.33	0.36
Cyclotella	*mong. 3*				2	9	-1.85	0.19	-1.77	0.24	2.51	0.01	2.51	0.22
Cyclotella	*mong. 4*				2	62.25	-1.69	0.14	-1.64	0.23	3.98	0.00	3.97	0.24
Cymatopleura	*solea*			(Bréb. & Godey) W.Sm.	6	0.75	-0.99	0.50	-0.99	0.42	3.23	0.37	3.22	0.34
Cymbella	*neoleptoceros*			Krammer	4	4.25	-1.45	0.16	-1.48	0.16	2.66	0.62	2.75	0.55
Denticula	*kuetzingii*			Grunow	8	13	-1.51	0.28	-1.51	0.25	2.51	0.23	2.51	0.23
Diatoma	*tenue*			C. Agardh	7	17.75	-1.53	0.20	-1.55	0.16	3.64	0.21	3.66	0.19
Discostella	*pseudostelligera*			(Hust.) Houk & Klee	9	47.75	-1.49	0.14	-1.46	0.16	3.45	0.38	3.33	0.44
Encyonema	*minutum*			(Hilse in Rabenhorst) D.G. Mann in Round, Crawford & Mann	9	0.75	-1.31	0.34	-1.29	0.30	2.46	0.28	2.48	0.25
Encyonopsis	*cesatii*			(Rabenh.) Krammer	4	20.75	-1.54	0.09	-1.53	0.11	2.47	0.10	2.47	0.13
Encyonopsis	*microcephala*			(Grunow) Krammer	13	14.5	-1.55	0.22	-1.55	0.22	2.58	0.27	2.60	0.28
Entomoneis	*mong. 1*				9	4.75	-1.11	0.57	-1.13	0.44	3.88	0.23	3.86	0.24
Epithemia	*adnata*			(Kütz.) Bréb.	7	8.75	-0.90	0.31	-0.97	0.27	2.99	0.43	3.09	0.38
Epithemia	*sorex*			Kütz.	6	4.5	-0.89	0.61	-1.03	0.41	2.81	0.53	2.88	0.47
Fallacia	*pygmaea*			(Kütz.) Stickle & D.G. Mann in Round, Crawford & Mann	13	2.75	-0.97	0.55	-1.02	0.49	3.74	0.54	3.72	0.52
Fragilaria	*capucina*			Desm.	6	1.25	-1.29	0.19	-1.29	0.18	3.18	0.64	3.22	0.56
Fragilaria	*vaucheriae*			(Kütz.) Petersen	13	2.5	-1.29	0.34	-1.29	0.33	2.56	0.43	2.58	0.43
Fragilaria	*nanana*			Lange-Bert.	2	24.5	-1.17	0.03	-1.18	0.19	2.98	0.22	2.90	0.29

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Fragilaria	*tenera*			(W. Smith) Lange-Bert.	14	15.5	-1.23	0.20	-1.24	0.21	2.62	0.35	2.60	0.31
Geissleria	*decussis*	*mong. 1*			2	44.75	-1.34	0.36	-1.20	0.29	2.45	0.43	2.27	0.34
Gomphonema	*angustatum*			(Kütz.) Rabenh.	10	20	-1.54	0.29	-1.53	0.29	2.56	0.46	2.62	0.45
Gomphonema	*auritum*			A. Braun ex Kütz.	3	2.75	-0.74	0.60	-0.81	0.39	2.96	0.39	2.91	0.32
Gomphonema	*gracile*			Ehrenb. emend. VanHeurck	3	1.75	-1.13	0.40	-1.19	0.33	2.64	0.33	2.59	0.31
Gomphonema	*mong. 1*				19	4.75	-0.82	0.45	-0.83	0.42	3.39	0.57	3.37	0.54
Gomphonema	*pumilum*			(Grunow) Reich. & Lange-Bert.	9	4.75	-0.80	0.44	-0.86	0.37	2.64	0.28	2.63	0.27
Gyrosigma	*obtusatum*			(Sulliv & Wormley) Boyer	2	4.75	-0.59	0.17	-0.59	0.25	3.27	0.91	3.27	0.58
Gyrosigma	*spenceri*			(Quek.) J.W.Griff. & Henfr.	7	8.5	-1.53	0.43	-1.44	0.37	4.21	0.38	4.13	0.33
Hippodonta	*capitata*			(Grunow) Lange-Bert., Metzelin & Witkowski	9	4.25	-0.85	0.51	-0.89	0.40	3.29	0.23	3.30	0.23
Hippodonta	*costulata*			(Grunow) Lange-Bert., Metzelin & Witkowski	2	7.75	-1.28	0.15	-1.31	0.23	2.51	0.15	2.48	0.26
Hippodonta	*hungarica*			(Grunow) Lange-Bert., Metzeltin & Witkowski	5	21.5	-1.52	0.22	-1.47	0.19	3.58	0.16	3.54	0.17
Hippodonta	*linearis*			(Østrup) Lange-Bert., Metzeltin & Witkowski	8	2.25	-1.16	0.58	-1.15	0.51	3.93	0.22	3.93	0.20
Karayevia	*clevei*			(Grunow in Cleve & Grunow) Round & Bukhtiyarova	3	6.5	-1.62	0.27	-1.56	0.24	2.86	0.42	2.72	0.36

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Martyana	*martyi*			(Héribaud) Round in Round, Crawford & Mann	8	27.5	-1.07	0.24	-1.09	0.20	2.60	0.44	2.66	0.39
Mastogloia	*elliptica*			(Agardh) Cleve in Schmidt et al.	3	1.25	-1.49	0.14	-1.51	0.18	2.66	0.59	2.77	0.53
Mastogloia	*smithii*	*lacustris*		Grunow	1	5.75	-1.56	0.38	...	...	2.42	0.43	...	...
Mastogloia	*smithii*			Thwaites	3	1	-1.62	0.04	-1.62	0.11	2.51	0.55	2.59	0.50
Navicula	*capitatoradiata*			Germain	3	3	-0.75	0.74	-0.84	0.46	2.56	0.61	2.65	0.56
Navicula	*cincta*			(Ehrenb.) Ralfs	17	11.75	-1.15	0.39	-1.13	0.37	3.48	0.38	3.48	0.37
Navicula	*concentrica*			J.W. Bailey	3	2.25	-1.76	0.37	-1.76	0.30	2.53	0.25	2.47	0.30
Navicula	*cryptocephala*			Kütz.	5	1.25	-1.28	0.36	-1.25	0.33	3.01	0.67	3.09	0.51
Navicula	*cryptotenella*			Lange-Bert.	20	20.5	-1.25	0.41	-1.26	0.38	2.95	0.66	2.95	0.61
Navicula	*digitoradiata*			(Greg.) Ralfs in A.Pritch.	2	1.75	-0.79	0.94	-0.89	0.55	3.63	0.76	3.71	0.51
Navicula	*eidrigiana*			Carter	3	1	-0.72	0.33	-0.75	0.30	3.64	0.61	3.59	0.48
Navicula	*germainii*			Wallace	4	2.25	-1.20	0.09	-1.19	0.12	3.16	0.38	3.13	0.33
Navicula	*libonensis*			Schoeman	2	4.75	-0.63	0.54	-0.76	0.39	2.60	0.04	2.59	0.22
Navicula	*menisculus*			Schum.	4	3.5	-1.16	0.53	-1.26	0.36	2.57	0.32	2.51	0.28
Navicula	*menisculus*	*upsaliensis*		(Grunow in Cleve & Grunow) Grunow in VanHeurck	7	1.75	-1.30	0.37	-1.29	0.33	2.61	0.31	2.60	0.28
Navicula	*oblonga*			(Kütz.) Kütz.	7	2.5	-1.30	0.40	-1.35	0.31	3.63	0.44	3.63	0.40
Navicula	*phyllepta*			Kütz.	9	11	-1.34	0.31	-1.36	0.30	4.33	0.23	4.30	0.20
Navicula	*radiosa*			Kütz.	13	4.5	-1.35	0.30	-1.34	0.27	2.60	0.34	2.61	0.30
Navicula	*salinarum*			Grunow	10	4.5	-0.72	0.50	-0.76	0.44	3.39	0.70	3.42	0.65
Navicula	*schoenfeltii*			Hust.	3	1	-1.81	0.17	-1.81	0.19	2.13	0.46	2.12	0.39

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Navicula	*veneta*			Kütz.	7	1.75	-1.10	0.42	-1.07	0.34	3.39	0.30	3.38	0.29
Navicymbula	*pusilla*			(Grunow) Krammer	14	80	-1.13	0.25	-1.14	0.23	4.35	0.21	4.32	0.22
Nitzschia	*angustata*			(W.Sm.) Grunow	7	9.75	-0.75	0.70	-0.98	0.46	2.61	0.33	2.61	0.30
Nitzschia	*bacillum*			Hust.	26	55	-0.76	0.38	-0.76	0.38	3.83	0.37	3.82	0.36
Nitzschia	*constricta*			(Kütz.) Ralfs	18	9.25	-1.04	0.52	-1.04	0.48	3.81	0.47	3.80	0.44
Nitzschia	*dissipata*			(Hantzsch) Grunow	8	1	-1.19	0.29	-1.19	0.26	2.66	0.60	2.67	0.53
Nitzschia	*frustulum*			(Kütz.) Grunow	9	4	-0.88	0.53	-0.91	0.49	3.08	0.76	3.09	0.72
Nitzschia	*frustulum*	*mong. 1*			10	17	-1.03	0.34	-1.08	0.33	4.04	0.48	3.95	0.46
Nitzschia	*graciliformis*			Lange-Bert. & Simonsen	8	22	-1.34	0.37	-1.33	0.34	3.26	0.52	3.21	0.46
Nitzschia	*inconspicua*			Grunow	17	5.5	-1.01	0.53	-1.02	0.51	3.64	0.47	3.64	0.45
Nitzschia	*lacuum*			Lange-Bert.	27	69.25	-1.05	0.47	-1.07	0.46	3.79	0.71	3.74	0.69
Nitzschia	*levidensis*	*salinarum*		Grunow	7	2.5	-1.24	0.60	-1.21	0.51	3.71	0.59	3.65	0.49
Nitzschia	*liebetruthii*			Rabenh.	14	66.75	-0.60	0.38	-0.65	0.34	3.81	0.22	3.81	0.22
Nitzschia	*obtusa*	*schweinfurthii*		(Grunow) Grunow in Cleve & Grunow	4	9.25	-1.30	0.35	-1.45	0.21	4.48	0.21	4.39	0.18
Nitzschia	*palea*			(Kütz.) W.Sm.	4	12	-1.02	0.19	-1.07	0.16	3.29	0.58	3.13	0.41
Nitzschia	*pusilla*			Grunow	3	2.75	-0.85	0.56	-0.88	0.43	3.88	0.64	3.91	0.48
Nitzschia	*recta*			Hantzsch ex Rabenh.	5	1	-1.13	0.64	-1.20	0.44	2.33	0.30	2.30	0.25
Nitzschia	*sublinearis*			Hust.	5	2.25	-1.35	0.39	-1.33	0.31	3.19	0.80	3.19	0.66
Nitzschia	*thermaloides*			Hust.	7	2.25	-0.80	0.50	-0.81	0.45	3.78	0.39	3.81	0.36
Nitzschia	*mong. 1*				14	7.25	-1.11	0.40	-1.11	0.37	3.42	0.34	3.42	0.34
Nitzschia	*mong. 2*				12	31.25	-0.82	0.47	-0.84	0.43	3.89	0.36	3.88	0.33
Nitzschia	*mong. 3*				6	2	-1.48	0.22	-1.49	0.18	2.68	0.63	2.66	0.49

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Opephora	*mong. 1*				16	46.75	-1.00	0.41	-1.02	0.35	3.39	0.90	3.34	0.72
Opephora	*mong. 2*				10	25	-0.76	0.72	-0.80	0.63	3.97	0.61	3.93	0.60
Opephora	*mong. 3*				7	19.5	-1.01	0.86	-0.94	0.65	4.06	0.24	4.06	0.18
Opephora	*mong. 4*				8	21	-0.28	0.76	-0.48	0.53	4.07	0.62	3.91	0.47
Opephora	*mong. 5*				1	12.5	-0.71	0.38	...	...	4.09	0.43	...	...
Parlibellus	*crucicula*			(W.Sm.) Witkowski, Lange-Bert.& Metzeltin	6	0.5	-0.96	0.34	-0.95	0.31	3.46	0.57	3.45	0.50
Pinnularia	*brebissonii*			(Kütz.) Rabenh.	8	3.75	-1.08	0.43	-1.09	0.40	3.68	0.33	3.70	0.30
Planothidium	*delicatulum*			(Kütz.) Round & Bukhtiyarova	11	2.25	-0.88	0.56	-0.88	0.53	3.77	0.40	3.78	0.38
Planothidium	*dubium*			(Grunow) Round & Bukhtiyarova	4	5.75	-1.19	0.37	-1.14	0.32	3.44	0.25	3.50	0.22
Planothidium	*frequentissimum*			(Lange-Bert. in Krammer & Lange-Bert.) Lange-Bert.	10	19	-1.22	0.30	-1.17	0.26	2.85	0.61	2.91	0.49
Psammothidium	*cf. sacculum*			(Carter) Bukhtiyarova	9	11.5	-1.65	0.16	-1.64	0.16	2.33	0.50	2.40	0.47
Pseudostaurosira	*brevistriata*			(Grunow in VanHeurck) Williams & Round	27	50.75	-1.54	0.36	-1.52	0.35	3.09	0.83	3.06	0.72
Pseudostaurosira	*polonica*			(Witak & Lange-Bert.) Morales & M.B. Edlund	15	20.5	-1.29	0.36	-1.31	0.35	2.68	0.49	2.72	0.48
Pseudostaurosira	*pseudosconstruens*			(Marciniak) Williams & Round	5	1.75	-1.46	0.39	-1.45	0.36	1.97	0.32	1.98	0.29
Pseudostaurosira	*subsalina*			(Hust.) Morales	4	10	-1.22	0.29	-1.16	0.30	3.32	0.36	3.28	0.40

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Pseudostaurosira	*elliptica*			(Schumann) M.B. Edlund, Morales & Spaulding	20	19.75	-1.48	0.38	-1.48	0.35	3.02	0.97	2.98	0.80
Rhoicosphenia	*abbreviata*			(C. Agardh) Lange-Bert.	18	13.5	-1.02	0.44	-1.04	0.41	3.16	0.54	3.19	0.51
Rhopalodia	*gibba*			(Ehrenb.) O.Müll.	10	2	-1.17	0.39	-1.18	0.35	3.05	0.49	3.05	0.44
Sellaphora	*pupula*			(Kütz.) Mereschk.	7	0.75	-1.41	0.42	-1.40	0.37	2.58	0.76	2.61	0.68
Staurosira	*construens*	*binodis*		(Ehrenb.) P.B.Ham. in Ham., Poulin, Prévost, Angell & Edlund	7	29	-1.23	0.26	-1.30	0.20	2.33	0.16	2.32	0.18
Staurosira	*construens*	*pumila*		(Grunow) Kingston	10	36.5	-1.65	0.37	-1.60	0.35	2.19	0.67	2.30	0.53
Staurosira	*venter*	*mong. 1*			6	10	-1.59	0.33	-1.56	0.26	2.22	0.64	2.28	0.46
Staurosira	*venter*	*mong. 2*			21	49.6	-1.09	0.76	-1.12	0.66	2.52	1.02	2.56	0.85
Staurosira	*venter*	*mong. 3*			7	6.25	-1.58	0.41	-1.60	0.31	2.58	0.40	2.55	0.33
Staurosira	*construens*			Ehrenb.	13	7	-1.58	0.35	-1.57	0.33	2.29	0.36	2.30	0.34
Staurosira	*construens*	*mong. 1*			6	6.5	-1.52	0.34	-1.52	0.31	2.33	0.35	2.36	0.29
Staurosira	*construens*	*mong. 2*			5	19.5	-1.41	0.21	-1.39	0.21	2.13	0.30	2.14	0.26
Staurosirella	*lapponica*				4	21.5	-1.52	0.29	-1.51	0.21	2.17	0.18	2.22	0.22
Staurosirella	*pinnata*	*intercedens*		(Grunow in VanHeurck)	5	2.25	-1.03	0.55	-1.01	0.49	2.49	0.51	2.49	0.47
Staurosirella	*pinnata*	*lancettula*		(Schumann) E.Y.Haw. & M.G.Kelly	6	1.25	-1.56	0.23	-1.55	0.21	2.43	0.42	2.42	0.34
Staurosirella	*pinnata*			Ehrenb.	34	68	-1.36	0.32	-1.35	0.31	2.35	0.50	2.37	0.50
Stephanodiscus	*minutulus*			(Kütz.) Cleve & J.D.Möll.	18	48.75	-1.01	0.36	-1.01	0.33	2.80	0.42	2.81	0.40

Genus	species	variety	form	authority	# lakes	Max	log TP Opt.	log TP Tol.	log TP Opt. (boot)	log TP Tol. (boot)	log SC Opt.	log SC Tol.	log SC Opt. (boot)	log SC Tol. (boot)
Surirella	*brebissonii*			Krammer & Lange-Bert.	7	1.75	-1.24	0.65	-1.23	0.55	3.82	0.35	3.83	0.32
Surirella	*brightwellii*			W. Sm.	8	1.75	-1.03	0.51	-1.02	0.45	3.37	0.66	3.39	0.56
Surirella	*peisonis*			Pant.	5	13	-0.87	0.26	-0.79	0.20	3.57	0.25	3.62	0.22
Synedra	*radians*			Kütz.	2	30.5	-1.17	0.48	-1.35	0.32	2.99	0.34	2.86	0.32
Synedra	*parasitica*			(W. Sm.) Hust.	7	4	-1.42	0.51	-1.33	0.42	2.71	0.46	2.60	0.37
Tabularia	*fasciculata*			(C.Agardh) D.M.Williams & Round	1	6	-1.39	0.38	...	...	3.53	0.43	...	...

Appendix 2-1: A list of all species oberved in calibration set lakes with the number of occurrences and maximum relative abundance. Species used in the calibration set (Chapter 1) and species which have not previously been reported from Mongolia (Edlund et al. 2001) are denoted with an ‘x’.

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Achnanthes	*bahusiensis*			(Grunow) Lange-Bert.	x	x	3	1.25
Achnanthes	*conspicua*			Mayer			1	0.25
Achnanthes	*holsatica*			Hust.		x	2	1.50
Achnanthes	*laevis*			Østrup		x	1	0.25
Achnanthes	*minuscula*			Hust.	x	x	2	1.25
Achnanthes	*ziegleri*			Lange-Bert.		x	3	0.50
Achnanthes	*brevipes*			C. Agardh			3	0.50
Achnanthes	*hungarica*			Grunow (Grunow)		x	1	0.25
Achnanthes	*jourascence*			Heribaud		x	2	0.50
Achnanthes	*levanderi*			Hust.		x	1	0.25
Achnanthes	*peragalli*			Brun & Heribaud		x	1	0.25
Achnanthes	*rosenstockii*			Lange-Bert.		x	3	1.75
Achnanthes	*mong. 1*					x	1	0.50
Achnanthes	*cf. grischuna*					x	3	0.50
Achnanthes	*grischuna*			Wuthrich		x	2	0.25
Achnanthidium	*exiguum*			(Grunow) Czarn.	x		5	0.75
Achnanthidium	*minutissimum*	*inconspicua*		Øestrup		x	2	1.25
Achnanthidium	*minutissimum*			(Kütz.) Czarn.	x		27	7.50
Amphora	*coffeaeformis*			(C.Agardh) Kütz.	x	x	15	47.75

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Amphora	*coffeaeformis*	*var. 1*				x	1	1.50
Amphora	*coffeaeformis*	*var. 2*				x	1	0.25
Amphora	*commutata*			Grunow	x		7	0.75
Amphora	*aequalis*			Krammer	x	x	2	6.00
Amphora	*inariensis*			Krammer	x	x	20	24.25
Amphora	*libyca*			Ehrenb.	x	x	32	13.00
Amphora	*ovalis*			(Kütz.) Kütz.	x		7	2.25
Amphora	*perpusilla*			(Grunow) Grunow in VanHeurck	x		31	46.50
Amphora	*thumensis*			(Mayer) A.Cleve	x		7	3.50
Amphora	*unknown 1*				x	x	3	1.50
Amphora	*unknown 2*				x	x	2	1.75
Amphora	*unknown 3*					x	3	13.25
Amphora	*veneta*	*capitata*		E.Y.Haw.	x	x	7	1.25
Amphora	*veneta*			Kütz.	x		5	1.50
Anomoeoneis	*sphaerophora*			(Ehrenb.) Pfitz.	x		8	5.00
Anomoeoneis	*sphaerophora*		*costata*	(Kütz.) A.M.Schmid	x		11	11.50
Asterionella	*formosa*			Hass.	x		2	9.25
Aulacoseira	*ambigua*			(Grunow) Simonsen			4	1.25
Aulacoseira	*granulata*			(Ehrenb.) Simonsen			1	1.25
Brachysira	*vitrea*			(Grunow) R.Ross in B.Hartley	x	x	3	2.00
Brachysira	*aponina*			Kütz.	x		2	9.75
Brachysira	*liliana*			Lange-Bert.	x	x	3	2.00
Brachysira	*unknown 1*					x	1	0.50

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Caloneis	*bacillum*			(Grunow) Cleve	x		5	0.75
Caloneis	*schumanniana*	*lancettula*		Hust.	x	x	2	1.00
Caloneis	*schumanniana*			(Grunow) Cleve	x	x	6	0.75
Caloneis	*silicula*			(Ehrenb.) P.T. Cleve			2	1.00
Campylodiscus	*bicostatus*			W.Sm. in Roper			1	1.50
Campylodiscus	*clypeus*			Ehrenb.			2	0.25
Chaetoceros	*mong. 1*				x	x	5	3.00
Chaetoceros	*mong. 2*				x	x	2	3.50
Cocconeis	*disculus*			(Schum.) P.T. Cleve in P.T. Cleve & Jentzsch			1	0.25
Cocconeis	*neothumensis*			Krammer	x	x	17	6.50
Cocconeis	*pediculus*			Ehrenb.	x		3	9.25
Cocconeis	*placentula*	*euglypta*		(Ehrenb.) Grunow	x		20	8.50
Cocconeis	*placentula*	*klinoraphis*		Geitler		x	1	0.50
Cocconeis	*placentula*	*lineata*		(Ehrenb.) VanHeurck	x		27	14.25
Cocconeis	*placentula*	*baicalensis*		Skvortzow	x	x	3	25.25
Craticula	*accomoda*			Hust.		x	2	0.50
Craticula	*ambigua*			(Ehrenb.) D.G.Mann in Round, Crawford & Mann	x	x	4	63.25
Craticula	*cuspidata*			Kütz(Kütz)		x	4	0.50
Craticula	*halophila*			(Grunow) D.G. Mann in Round, Crawford & Mann	x	x	6	3.25
Ctenophora	*pulchella*			(Ralfs ex Kütz.) D.M.Williams & Round	x	x	10	1.75
Cyclotella	*choctawatcheeana*			Prasad	x	x	2	19.50
Cyclotella	*meneghiniana*			Kütz.			3	1.25

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Cyclotella	*ocellata*			Pant.	x		5	37.00
Cyclotella	*buyantsogii*			A.L.C. Shinneman, M.B. Edlund, M.L. Julius, N. Soninkhishig prov. nom	x	x	1	30.75
Cyclotella	*uuregensis*			A.L.C. Shinneman, M.B. Edlund, M.L. Julius, N. Soninkhishig prov. nom		x	1	100.00
Cyclotella	*siberica*			Skabitschebsky	x		1	9.00
Cymatopleura	*elliptica*	*hibernica*		*(W.Sm.) Van Heurck*		x	1	0.50
Cymatopleura	*elliptica*			(Bréb. in Kütz.) W. Sm.			1	0.25
Cymatopleura	*solea*	*apiculata*		*(W. Sm.) Ralfs*		x	1	0.25
Cymatopleura	*solea*			(Bréb. & Godey) W.Sm.	x		6	0.75
Cymbella	*affinis*			Kütz.		x	1	0.75
Cymbella	*amphicephala*			Nägeli			3	0.50
Cymbella	*cf. stigmaphora*					x	1	1.00
Cymbella	*cymbiformis*			C. Agardh			2	1.25
Cymbella	*ehrenbergii*			Kütz.			2	0.25
Cymbella	*hantzschiana*			Krammer		x	4	0.75
Cymbella	*helvetica*			Kütz.			1	0.75
Cymbella	*laevis*			Nägeli ex Kütz.			1	0.25
Cymbella	*neocistula*			Krammer		x	2	0.25
Cymbella	*neoleptoceros*			Krammer	x	x	4	4.25
Cymbella	*reinhardtii*			Grunow		x	1	0.25
Cymbella	*stigmaphora*			Østrup		x	1	2.00
Cymbella	*subaequalis*			Grunow			2	0.25
Cymbella	*subhelvetica*			Krammer		x	1	0.50

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Cymbella	*vulgata*			Krammer		x	1	0.25
Cymbella	*subleptoceros*			Krammer		x	2	0.25
Denticula	*kuetzingii*			Grunow	x	x	7	4.75
Denticula	*subtilis*			Grunow		x	1	1.00
Denticula	*tenuis*			Kütz.			1	13.00
Diatoma	*moniliformis*			Kütz.		x	1	1.75
Diatoma	*tenue*			C. Agardh	x		7	17.75
Diatoma	*vulgaris*			Bory			1	0.25
Diploneis	*elliptica*			(Kütz.) P.T. Cleve			2	0.25
Diploneis	*puella*			(Schum.) P.T. Cleve			1	0.25
Discostella	*pseudostelligera*			(Hust.) Houk & Klee	x		9	47.75
Encyonema	*minutum*		*latens*	(Krasske) C.W.Reimer		x	1	0.50
Encyonema	*minutum*			(Hilse in Rabenhorst) D.G. Mann in Round, Crawford & Mann	x	x	9	0.75
Encyonema	*silesiacum*			(Bleisch in Rabenhorst) Mann in Round, Crawford & Mann		x	1	0.25
Encyonema	*cf. silesiacum*					x	1	0.25
Encyonopsis	*cesatii*			(Rabenh.) Krammer	x		4	20.75
Encyonopsis	*microcephala*			(Grunow) Krammer	x		13	14.50
Entomoneis	*mong. 1*				x	x	9	4.75
Epithemia	*adnata*			(Kütz.) Bréb.	x		7	8.75
Epithemia	*frickei*			Krammer		x	1	0.50
Epithemia	*smithii*			Carruthers		x	3	2.75
Epithemia	*sorex*			Kütz.	x		6	4.50

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Eucocconeis	*flexella*			(Kütz.) Cleve			1	0.25
Eunotia	*septentrionalis*			Østrup		x	1	0.25
Fallacia	*pygmaea*			(Kütz.) Stickle & D.G. Mann in Round, Crawford & Mann	x		13	2.75
Fragilaria	*robusta*			(Fusey) Manguin		x	1	0.25
Fragilaria	*capucina*	*mesolepta*		(Rabenh.) Rabenh.			1	4.00
Fragilaria	*capucina*			Desm.	x		6	1.25
Fragilaria	*vaucheriae*			(Kütz.) Petersen	x		13	2.50
Fragilaria	*nanana*			Lange-Bert.	x	x	2	24.50
Fragilaria	*tenera*			(W. Smith) Lange-Bert.	x	x	14	15.50
Fragilaria	*vaucherie*			(Kütz.) J.B. Petersen			1	0.75
Fragilariforma	*virescens*			(Ralfs) D.M.Williams & Round			1	0.25
Geissleria	*decussis*	*mong. 1*			x	x	2	44.75
Geissleria	*schoenfeltii*			Hust.	x		3	1.00
Gomphonema	*angustum*			(Kütz.) Rabenh.	x		10	20.00
Gomphonema	*auritum*			A. Braun ex Kütz.	x	x	3	2.75
Gomphonema	*dichotomum*			Kütz.		x	2	0.25
Gomphonema	*gracile*			Ehrenb. emend. VanHeurck	x		3	1.75
Gomphonema	*herbidense*			Gregory		x	2	0.25
Gomphonema	*olivaceum*	*calcareum*		(P.T. Cleve) P.T. Cleve			4	1.75
Gomphonema	*mong. 1*				x	x	19	4.75
Gomphonema	*pumilum*			(Grunow) Reich. & Lange-Bert.	x	x	9	4.75
Gomphonema	*tenellum*			Kütz.			1	0.25

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Gomphonema	*truncatum*			Ehrenb.			2	0.50
Gomphonema	*utae*			Lange-Bert. & Reich.		x	1	4.25
Gomphonema	*parvulum*			Kütz.(Kütz.)			2	0.50
Gyrosigma	*obtusatum*			(Sulliv & Wormley) Boyer	x	x	2	4.75
Gyrosigma	*spenceri*			(Quek.) J.W.Griff. & Henfr.	x	x	7	8.50
Hantzschia	*amphioxis*			(Ehrenb.) Grunow			3	6.00
Hantzschia	*distinctepunctata*			(Hust.) Hust.		x	1	0.25
Hippodonta	*capitata*			(Grunow) Lange-Bert., Metzelin & Witkowski	x		9	4.25
Hippodonta	*costulata*			(Grunow) Lange-Bert., Metzelin & Witkowski	x		2	7.75
Hippodonta	*hungarica*			(Grunow) Lange-Bert., Metzeltin & Witkowski	x		5	21.50
Hippodonta	*linearis*			(Østrup) Lange-Bert., Metzeltin & Witkowski	x	x	8	2.25
Hippodonta	*subcostulata*			(Hust.) Lange-Bert., Metzelin & Witkowski		x	1	0.75
Karayevia	*clevei*			(Grunow in Cleve & Grunow) Round & Bukhtiyarova	x		3	6.50
Karayevia	*clevei*	*rostrata*		(Hust.) J.C. Kingston			1	0.75
Luticola	*mutica*			Kütz.		x	2	14.25
Martyana	*martyi*			(Héribaud) Round in Round, Crawford & Mann	x		8	27.50
Mastogloia	*elliptica*			(Agardh) Cleve in Schmidt et al.	x	x	3	1.25
Mastogloia	*smithii*	*amphicephala*		Grunow		x	1	0.25
Mastogloia	*smithii*	*lacustris*		Grunow	x	x	1	5.75

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Mastogloia	*smithii*			Thwaites	x		3	1.00
Melosira	*monofiliformis*			(O.F. Müller) Agardh		x	1	0.25
Navicula	*absoluta*			Hust.		x	1	0.25
Navicula	*capitatoradiata*			Germain	x		3	3.00
Navicula	*cari*			Ehrenb.		x	4	1.00
Navicula	*cincta*			(Ehrenb.) Ralfs	x		17	11.75
Navicula	*clementis*			Grunow		x	1	0.50
Navicula	*clementoides*			Hust.		x	2	0.50
Navicula	*concentrica*			J.W. Bailey	x	x	3	2.25
Navicula	*cryptocephala*			Kütz.	x		5	1.25
Navicula	*cryptotenella*			Lange-Bert.	x	x	20	20.50
Navicula	*digitoradiata*			(Greg.) Ralfs in A.Pritch.	x	x	2	1.75
Navicula	*diluviana*			Krasske		x	4	3.25
Navicula	*eidrigiana*			Carter	x	x	3	1.00
Navicula	*elegans*			W.Sm.		x	1	1.25
Navicula	*germainii*			Wallace	x	x	4	2.25
Navicula	*gottlandica*			Grunow		x	2	1.75
Navicula	*gregaria*			Donkin		x	1	1.25
Navicula	*humerosa*			Breb. ex W. Sm.			1	0.25
Navicula	*incerta*			Grunow		x	1	0.25
Navicula	*jaernfeltdii*			Hust.		x	2	0.25
Navicula	*jentzschii*			Grunow		x	1	0.75
Navicula	*libonensis*			Schoeman	x	x	2	4.75
Navicula	*menisculus*			Schum.	x		4	3.50

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Navicula	*menisculus*	*upsaliensis*		(Grunow in Cleve & Grunow) Grunow in VanHeurck	x		7	1.75
Navicula	*minima*			Grunow in Van Heurck		x	1	0.25
Navicula	*moskalii*			Metzeltin, Witkowski & Lange-Bert.		x	1	0.25
Navicula	*oblonga*			(Kütz.) Kütz.	x		7	2.50
Navicula	*phyllepta*			Kütz.	x		9	11.00
Navicula	*placentula*			(Ehrenberg) Grunow		x	3	0.75
Navicula	*praeterita*			Hust.		x	4	0.50
Navicula	*protracta*			(Grunow in P.T. Cleve & Grunow) P.T. Cleve			1	0.25
Navicula	*pseudolanceolata*			Lange-Bert.		x	2	1.25
Navicula	*pseudoscutiformis*			Hust.		x	1	0.25
Navicula	*pseudanglica*			Lange-Bert.		x	3	0.50
Navicula	*pseudoventralis*			Hust.		x	1	0.25
Navicula	*pseudotuscula*			Hust.		x	3	0.25
Navicula	*radiosa*			Kütz.	x		13	4.50
Navicula	*recens*			(Lange-Bert.) Lange-Bert.		x	1	2.00
Navicula	*reinhardtii*			Grunow in P.T. Cleve & J.D. Möller			4	1.75
Navicula	*rhynchocephala*			Kütz.			1	0.25
Navicula	*salinarum*			Grunow	x		10	4.50
Navicula	*scutelloides*			W. Sm.		x	1	0.50
Navicula	*slesvicensis*			Grunow		x	1	0.75
Navicula	*subplacentula*			Hust.		x	2	0.75

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Navicula	*subrotunda*			Hust.		x	1	4.00
Navicula	*tenelloides*			Hust.		x	1	0.25
Navicula	*trivialis*			Lange-Bert.		x	2	3.75
Navicula	*trophicatrix*			Lange-Bert.		x	1	1.25
Navicula	*veneta*			Kütz.	x	x	7	1.75
Navicula	*vitabunda*			Hust.		x	1	1.00
Navicymbula	*pusilla*			(Grunow) Krammer	x	x	14	80.00
Neidium	*ampliatum*			(Ehrenb.) Krammer in Krammer & Lange-Bert.		x	1	0.25
Neidium	*distincte-punctatum*			Hust.		x	1	0.50
Nitzschia	*acuminata*			(W.Sm.) Grunow		x	1	0.25
Nitzschia	*angustata*			(W.Sm.) Grunow	x		7	9.75
Nitzschia	*bacillum*			Hust.	x	x	27	55.00
Nitzschia	*bergii*			Hust.		x	1	6.00
Nitzschia	*commutata*			Grunow		x	2	2.00
Nitzschia	*constricta*			(Kütz.) Ralfs	x	x	18	9.25
Nitzschia	*dissipata*	*media*		(Hantzsch) Grunow		x	1	0.25
Nitzschia	*dissipata*			(Hantzsch) Grunow	x		8	1.00
Nitzschia	*eglei*			Lange-Bert.		x	1	1.75
Nitzschia	*frustulum*			(Kütz.) Grunow	x		9	4.00
Nitzschia	*frustulum*	*mong. 1*			x	x	10	17.00
Nitzschia	*graciliformis*			Lange-Bert. & Simonsen	x	x	8	22.00
Nitzschia	*heufleriana*			Grunow		x	1	0.50
Nitzschia	*inconspicua*			Grunow	x	x	17	5.50
Nitzschia	*lacuum*			Lange-Bert.	x	x	27	69.25

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Nitzschia	*levidensis*	*salinarum*		Grunow	x	x	7	2.50
Nitzschia	*liebetruthii*			Rabenh.	x	x	14	66.75
Nitzschia	*obtusa*	*schweinfurthii*		(Grunow) Grunow in Cleve & Grunow	x	x	4	9.25
Nitzschia	*palea*			(Kütz.) W.Sm.	x		4	12.00
Nitzschia	*pura*			Hust.		x	3	3.25
Nitzschia	*pusilla*			Grunow	x	x	3	2.75
Nitzschia	*recta*			Hantzsch ex Rabenh.	x	x	5	1.00
NItzschia	*sigmoidea*			(Nitzsch) W. Sm.			2	1.00
Nitzschia	*sublinearis*			Hust.	x		5	2.25
Nitzschia	*thermaloides*			Hust.	x	x	7	2.25
Nitzschia	*mong. 1*				x	x	14	7.25
Nitzschia	*mong. 2*				x	x	12	31.25
Nitzschia	*mong. 3*				x	x	6	2.00
Nitzschia	*acicularis*			(Kütz.) W. Sm.			1	3.75
Nitzschia	*amphibia*			Grunow			1	0.50
Nitzschia	*intermedia*			Hantzsch		x	3	0.50
Nitzschia	*linearis*			(C. Agardh) W.Sm.			3	1.00
Nitzschia	*linearis*	*subtilis*		(Grunow) Hust.		x	1	0.25
Nitzschia	*paleacea*			Grunnow in Van Heurck			2	0.25
Nitzschia	*perminuta*			(Grunow) Perag.			2	1.50
Opephora	*mong. 1*				x	x	16	46.75
Opephora	*mong. 2*				x	x	10	25.00
Opephora	*mong. 3*				x	x	7	19.50
Opephora	*mong. 4*				x	x	8	21.00

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Opephora	*mong. 5*				x	x	1	12.50
Parlibellus	*crucicula*			(W.Sm.) Donkin	x		6	0.50
Navicula	*crucicula*	*cruciculoides*		Brockmann		x	3	3.25
Pinnularia	*brebissonii*			(Kütz.) Rabenh.	x		8	3.75
Pinnularia	*lundii*			Hust.		x	1	0.75
Pinnularia	*subrostrata*			(A.Cleve) A.Cleve		x	1	0.25
Pinnularia	*viridiformis*			Krammer		x	1	0.25
Pinnularia	*microstauron*			(Ehrenb.) P.T. Cleve			1	1.25
Pinnularia	*petersenii*			Krammer & Lange-Bert.		x	1	3.50
Planothidium	*delicatulum*			(Kütz.) Round & Bukhtiyarova	x		11	2.25
Planothidium	*lanceolatum*	*biporoma*		(Hohn & Hellermann) Lange-Bert.		x	1	0.25
Planothidium	*lanceolatum*			(Bréb. ex Kütz.) Round			5	0.50
Planothidium	*dubium*			(Grunow) Round & Bukhtiyarova	x		4	5.75
Planothidium	*frequentissimum*			(Lange-Bert. in Krammer & Lange-Bert.) Lange-Bert.	x	x	10	19.00
Planothidium	*lanceolatum*	*rostrata*		(Østrup) Hust.		x	1	0.25
Pleurosigma	*australe*			Grunow		x	1	0.25
Pleurosigma	*salinarum*			Grunow		x	1	0.25
Psammothidium	*bioretti*			(H. Germ.) Bukhtiyarova & Round			3	0.50
Psammothidium	*cf. sacculum*			(Carter) Bukhtiyarova	x	x	9	11.50
Pseudostaurosira	*brevistriata*	*inflata*		(Hust.) Williams & Round		x	1	2.25

Genus	**species**	**variety**	**form**	**Authority**	**Calibration Set**	**New Report**	**# of lakes**	**max. %**
Pseudostaurosira	*brevistriata*			(Grunow in VanHeurck) Williams & Round	x		27	50.75
Pseudostaurosira	*elliptica*	*var. 1*					3	4.00
Pseudostaurosira	*elliptica*			(Schumann) M.B. Edlund, Morales & Spaulding	x	x	20	19.75
Pseudostaurosira	*polonica*			(Witak & Lange-Bert.) Morales & M.B. Edlund	x	x	15	20.50
Pseudostaurosira	*pseudosconstruens*			(Marciniak) Williams & Round	x	x	5	1.75
Pseudostaurosira	*subsalina*			(Hust.) Morales	x	x	4	10.00
Puncticulata	*khyargusiana*			A.L.C. Shinneman, M.B. Edlund, M.L. Julius, N. Soninkhishig, prov. nom.	x	x	1	100.00
Puncticulata	*radiosa*			(Lemmerman) Håkkansson	x	x	27	53.00
Reimeria	*sinuata*			Gregory (Kociolek & Stoermer)		x	2	0.75
Rhoicosphenia	*abbreviata*			(C. Agardh) Lange-Bert.	x	x	18	13.50
Rhopalodia	*gibba*			(Ehrenb.) O.Müll.	x		10	2.00
Sellaphora	*pupula*			(Kütz.) Mereschk.	x		8	0.75
Sellaphora	*bacillum*			(Ehrenb.) D.G. Mann			1	0.75
Sellaphora	*auldreekie*			D. G. Mann & S. M. McDonald		x	3	0.50
Stauroneis	*anceps*	*gracilis*		Rabenh.			1	1.50
Stauroneis	*smithii*			Grunow			2	0.50
Staurosira	*construens*	*binodis*		(Ehrenb.) P.B.Ham. in Ham., Poulin, Prévost, Angell & Edlund	x	x	7	29.00

Genus	species	variety	form	Authority	Calibration Set	New Report	# of lakes	max. %
Staurosira	*construens*			Ehrenb.	x		13	7.00
Staurosira	*construens*	*mong. 1*			x	x	6	6.50
Staurosira	*construens*	*mong. 2*			x	x	5	19.50
Staurosira	*construens*	*subsalina*		Hust.			3	1.00
Staurosira	*construens*	*trinodis*		(Ehrenb.) P.B.Ham. in Ham., Poulin, Prévost, Angell & Edlund		x	1	0.25
Staurosira	*construens*	*pumila*		(Grunow) Kingston	x		11	36.50
Staurosira	*venter*	*mong. 1*			x	x	6	10.00
Staurosira	*venter*	*mong. 2*			x	x	21	32.75
Staurosira	*venter*	*mong. 3*			x	x	7	6.25
Staurosirella	*lapponica*			(Grunow in VanHeurck) D.M. Williams & Round)	x		4	21.50
Staurosirella	*oldenburgiana*			Hust. (Morales)		x	1	0.25
Staurosirella	*pinnata*	*intercedens*		(Grunow in VanHeurck)	x	x	5	2.25
Staurosirella	*pinnata*	*lancettula*		(Schumann) E.Y.Haw. & M.G.Kelly	x	x	6	1.25
Staurosirella	*pinnata*			Ehrenb.	x		35	68.00
Stephanodiscus	*minutulus*			(Kütz.) Cleve & J.D.Möll.	x		19	48.75
Surirella	*bifrons*			Ehrenb.			1	0.25
Surirella	*brebissonii*			Krammer & Lange-Bert.	x	x	7	1.75
Surirella	*brightwellii*			W. Sm.	x	x	8	1.75
Surirella	*capronii*			Breb. in Kitton			1	0.50
Surirella	*minuta*			Breb. in Kütz.			1	0.50
Surirella	*peisonis*			Pant.	x		5	13.00
Synedra	*cyclopum*			Brutschy			2	0.75

Genus	**species**	**variety**	**form**	**Authority**	**Calibration Set**	**New Report**	**# of lakes**	**max. %**
Synedra	*parasitica*			(W. Sm.) Hust.			7	4.00
Synedra	*radians*			Kütz.	x		2	30.50
Synedra	*ulna*	*acus*		Kütz.		x	2	0.25
Synedra	*ulna*			(Nitzsch) Ehrenb.			2	0.50
Tabularia	*fasciculata*			(C.Agardh) D.M.Williams & Round	x	x	1	6.00