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Post-Glacial Chironomidae Population Responses to Climate-Driven Variations in Lake Production in the Canadian Arctic Archipelago

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Post-glacial Chironomidae population responses to climate-driven variations in lake production in the Canadian Arctic Archipelago

by
Marie-Claude Fortin

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Abstract

The purpose of this thesis was to study long-term climatic variations and their impacts on aquatic ecosystem functioning in the Canadian Arctic. Sub-fossil remains of chironomids preserved in lacustrine sediment cores, and the organic, biogenic silica and carbonate fraction of the sediment matrix were analyzed to infer past lake production and provide new evidence of the impact of past climate changes in the Arctic. The modern relationship between chironomids, biological production indices and the physical environment was studied to permit the interpretation and quantification of past conditions from sediment cores.

Bedrock composition exerts a very strong influence on sediment organic, biogenic silica and carbonate content of lake sediments, and an inference model for reconstructing lake water pH based on these parameters was developed. July air temperatures also affect aquatic and terrestrial production in the Arctic, but this effect is secondary to the effect of nutrient input. An inference model for reconstructing past mean July air temperatures based on the chironomid assemblages was developed using 88 Arctic lakes, and further improved by combining it with previously published data from across North America. A new inference model for July air temperatures, based on 379 Arctic and Boreal lakes was developed. This training set was based on sites covering a large temperature gradient (2°-16.6°C) and containing a great diversity of chironomid assemblages, making it appropriate for reconstructing past July air temperatures for Arctic and boreal lakes.

Holocene climatic conditions were evaluated for the Arctic at Lake WB02 (Northern Victoria Island), Lake KR02 (Western Victoria Island) and Lake JR01 (Boothia Peninsula). Prior to ~6.5-5.5ka the Arctic was relatively warm, and overall lake production was high. Mean July air temperatures remained colder during the mid- to late-Holocene until ~1.0ka,

when temperatures again cooled rapidly during the Little Ice Age. A recent (last 150 years) warming is seen at all three lakes as primary and chironomid production increased. At all locations, however, inferred temperatures for the last 150 years remain up to 2-3°C cooler than those inferred for the early Holocene.

Résumé

Le but de cette recherche fut d'évaluer l'impact de la variabilité climatique sur le fonctionnement des écosystèmes lacustres de l'Arctique canadien durant l'Holocène. Les fossiles de chironomides préservés dans les sédiments lacustres ainsi que le contenu de matière organique, de carbonate et de silice biogénique sédimentaire, furent analysés afin de mieux comprendre les changements de production lacustre et la variabilité du climat dans l'Arctique au cours de l'Holocène. Dans un contexte « néo-écologique » les rapports entre les chironomides, les indices de production biologique et les charactéristiques physiques de l'environnement ont été examinés afin de permettre l'interprétation et la quantification, à partir de carottes de sédiment, des conditions environmentales passées.

D'après nos recherches, nous avons déternimé que la composition de la roche de base influence très fortement le contenu de matière organique, de carbonate et de silice biogénique du sédiment lacustre. Ces relations nous ont permis de développer un modèle permettant la quantification dans le passé du pH lacustre. Les températures moyennes d'air du mois de juillet ont également une influence sur la production lacustre et terrestre, mais cette influence est moidre que celle excercée par l'apport de nutriments. Un model d'inférence permettant de prédire les températures moyennes d'air du mois de juillet passées a été dévelopé en se basant sur une série de 88 lacs de l'Arctique canadian. Par la suite, ce model fut amélioré en combinant les données de ces lacs arctiques à d'autre données de lacs

nord américains déjà publiées. Ainsi, un nouveau model d'inférence prédisant les températures moyennes d'air du mois de juillet, basé sur 379 lacs arctiques et boréaux, fut développé. Cette série de lacs inclue dans l'analyse recouvre une large gamme de températures (2°C à 16.6°C) et contient une grande variété d'assemblages de chironomides; permettant l'utlisation de ce model afin de prédire les températures moyennes d'air du mois de juillet passées, et ça pour tous les lacs arctiques et boréaux.

Les conditions climatiques de la prériode de l'Holocène furent évaluées au Lac WB02 (au nord de l'Île Victoria), Lac KR02 (à l'ouest de l'Île Victoria) et Lac JR01 (Péninsule Boothia) dans l'Arctique. Jusqu'à il y a environ 6,500-5,500 ans, le climat arctique était relativement chaud et la production lacustre était élevée. Les températures moyennes de l'air du mois de juillet demeurèrent plus froides de la mi- à la récente Holocène. A partir d'il y a environ 1,000 années, pendant le Petit Âge Glaciaire, les températures baissèrent. Récemment, au cours de dernières 150 années, la production primaire ainsi que celles des chironomides augmentèrent dans les trois lacs étudiés. Parcontre, les températures moyennes de l'air du mois de Juillet demeurèrent jusqu'à 2-3°C plus froides lors de ces dernières 150 années comparées à celles prédites pour le début de l'Holocène.

Dédicace

Je dédie cette thèse à mon père,
le Dr. Jean-Claude Fortin,
qui souvent me rappelle
de ne pas chercher midi à quatorze heure

Acknowledgments

Author: "Looks like we're in trouble KG"

Konrad Gajewski: "What do you mean *we*?"

I'd like to thank Dr. Konrad Gajewski, my tireless supervisor, for continually reminding me what "good science" is. I am proud to have worked with you and when all is said and done have to admit that you were right, *most* of the time. You encourage us all to always ask why, and continually remind us that "if it were easy, everybody would be doing it". There are simply not enough words.

My fellow LPCers, past and present, your support and friendship have been invaluable. You truly make the lab a place where scientific discussions are encouraged and where ideas, even the more contentious ones, are always exchanged freely. Joan, thanks for the continual help and support, all the way down the the final thesis cover page! To all the work studies, particularly Jessica McGuiness, Laura Robert and Enid Drummond who endured the BSi marathons, or days on end of chironomid picking, I cannot thank you enough, and yes the IOUs are still redeemable. Belle Berthilda je te remercie pour ton courage. A Jean Bjornson, technicien de laboratoire par excellence, sans qui je pense tout aurait été lâché au moins une douzaine de fois au cours des derniers 5 ans, un gros merci. I would also like to thank my committee members, Dr. Frances Pick, Dr. Jules Blais and Dr. Mike Pisaric, my external evaluator Dr. Gregory-Eaves as well as all the funding agencies (PCSP, NSTP, NSERC and OGS) who supported my research.

This master-tuned-into-PhD was a difficult but rewarding journey and through it all I could always turn to friends and family to offer advice. You were all great listeners, especially when I stopped making sense, so thank you for always being there. Tara Paull, being trapped with you for 7 days in a half broken tent in the Arctic is something I will never forget. Our talks out front in the grass about why transfer functions simply don't work for diatoms will have to be continued, and thanks for the maps and the scientific banter; we *are* huge nerds.

Je voudrais également remercier mes parents. Si Louise était toujours avec nous, j'imagine qu'elle serait soulagée et fière. Jean-Claude, finalement la moyenne est bonne, ouf.

En dernier, je voudrais remercier mon conjoint Peter. Tu as toujours cru en moi, surtout quand je me doutais le plus. Merci pour les relectures, les dîners au labo, les soirées passées au microscope ... si seulement tout le monde pouvait être aussi chanceux que moi.

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Chapter 1: Introduction

Purpose and objectives

The purpose of this thesis is to investigate long-term climatic variations and their impacts on aquatic ecosystem functioning in the Canadian Arctic. Using a paleolimnological approach, this thesis will focus on assemblages of lower trophic-level aquatic organisms (primarily chironomids) and inferred lake production in order to provide new evidence of the impact of climate change in the Arctic.

There are two general parts to this thesis which together will quantify the relationship between aquatic communities and their environment on long timescales. The first part will examine the relationship between the modern environment and sediment biological fossil and geochemical parameters in order to develop inference tools which can then be applied to fossil sediment records to provide new lines of evidence of past environmental changes. The second part will focus on examining the fossil records of chironomids and other proxies in three Arctic lakes to determine the past history of climatic changes in these regions, to contextualize the recent warming (last 150 years) at these sites and to assess the impact of climatic variability on these lacustrine ecosystems through the Holocene.

Chapters 2-7 of this thesis were written as independent papers and each contains a comprehensive review of the literature pertinent to the paper's specific topic. As such, the following overview is not intended to be exhaustive.

Study area: the Canadian Arctic

Since the beginning of the 19th century, the Canadian Arctic has been undergoing a significant warming, and general circulation models predict that air temperatures will increase the most at these higher latitudes (IPCC, 2007). Serreze et al. have recorded a 2-5°C increase in Arctic air temperatures since the 1960s (Serreze et al., 2000). These climate changes are having significant impacts on Arctic ecosystems. Increases in precipitation, permafrost and glacial melt, decreases in snow cover and albedo, and longer ice-free and growing seasons in lakes and other ecosystems have already been observed (IPCC, 2007). For lacustrine ecosystems in particular, further changes in aquatic production, species composition and overall functioning are expected as a result of changes in the lake's physical environment due to these climatic pressures (Smol et al., 1991). Furthermore, it is only recently—over the last 50 years—that changes in environmental conditions in the Arctic have been monitored and their impact on ecosystems examined. There is, therefore, no temporal context in which to place the recent changes observed in the Arctic.

Paleolimnological framework

In a paleolimnological study, the key to understanding the past is archived in the sediment matrix preserved at the bottom of lakes. Lake ecosystem functioning is influenced by physical and chemical changes, and these are affected by climate variability (Smol et al., 1991; Battarbee, 2000). Archives of this climatic variability are found within the lakes' sediments and the fossilized biota they contain (Quinlan et al., 2005). In this thesis and other paleolimnological work, surface sediments or long sediment sequences (cores) are obtained from lakes and the remains of organisms found in these sediments are extracted and used as proxy indicators of past climatic conditions (Smol and Douglas, 1996). For longer sequences, changes in these fossil organisms through time can be assessed and interpreted. This thesis will primarily assess chironomid fossils and geochemical parameters, including sediment parameters, in particular organic, carbonate and biogenic silica content preserved in the sediment matrix, as indicators of past conditions.

There remain a number of unresolved questions concerning the significance of the recent warming in the Arctic and what effects we can expect this warming to have on specific ecosystems within the Arctic region. The ability to answer these types of questions is what makes paleolimnological studies indispensable tools in an overall strategy of global change research. A paleolimnological analysis of past environmental conditions can provide a context within which one can assess present changes in temperature, as well as detailed insights into how the important lacustrine ecosystem characteristics (such as overall production, species composition and the interaction between organisms and different trophic levels) have been affected by changes in the past environment. Understanding the dynamics of the past will generate insights for the future.

Chironomids

This thesis focuses primarily on the changes in chironomid assemblages through time by examining their preserved remains in lake sediment sequences. Chironomids are among the most abundant insects found in aquatic environments. The immature stages (larvae) of chironomids develop chitinous head capsules, which are preserved in various kinds of sediments and provide an important tool for paleolimnologists interested in understanding past environmental change (Oliver and Roussel, 1983). The larvae are generally macrophagous and feed on algae (mostly diatoms), bacteria, organic material, detritus, macrophytes and other invertebrates (Oliver, 1971). Changes in the environment directly influence the abundance and distribution of the chironomid populations and communities. Their species composition is also affected by changes in environmental conditions, as different chironomid taxa have different environmental tolerances. These changes in community assemblages through time are "recorded" in the sediment sequence and can be examined by extracting the chironomid fossil remains from the sediment matrix. For this reason, chironomids are frequently used in paleoecological work as biological indicators of a number of environmental parameters including but not limited to: water temperature, hypolimnetic oxygen content, salinity and lake depth, as well as lake trophic levels and air temperature (Olander et al., 1997; Walker et al., 1997; Lotter et al., 1998; Battarbee, 2000; Brooks and Birks, 2000; Clerk et al., 2000; Brooks et al., 2001; Walker, 2001).

Reconstruction methodology

The first step in using down-core chironomid assemblages to infer past environmental conditions is the creation of a modern chironomid calibration set (Birks and Birks, 1980). These calibration datasets, also known as "modern training sets", are produced by sampling the top few centimeters of sediment from a large number of lakes (Smol, 2002). The chironomid head capsules in the sediment are picked and identified, and the relative abundance of the taxa can be determined from these assemblages. Using a series of lakes, the geographic distribution of the taxa can be mapped. The water chemistry and environmental conditions are documented at each of these lakes, making it possible to associate each modern chironomid assemblage with specific environmental conditions. Ideally, a modern calibration set provides a modern analogue for every chironomid fossil assemblage found downcore (Seppa and Bennett, 2003).

Through correlation analysis, it is also possible to determine which environmental variables are most closely correlated to the modern-day chironomid distribution and abundance. The use of modern analogues and the correlation between environmental variables and modern chironomid assemblages are the basis for two techniques used for the quantitative reconstruction of past environments, the Modern Analogue Technique (MAT) and a series of "transfer function" methods such as Weighted Averaging Partial Least Squared (WAPLS). By using the MAT or applying these transfer functions to the relative abundance data of chironomid taxa downcore, quantitative estimates of past environmental conditions such as mean July air temperature or lake water pH can be reconstructed through time. Mean July air temperatures are often reconstructed as climate models use these as representative temperatures for the height of the growing season.

Chironomid-based training sets that contain Canadian Arctic lakes include Walker et al. (1997) from eastern Canada, Wilson et al. (2004) from the Yukon/BC, Gajewski et al. (2005) from the Canadian Arctic Islands, Barley et al. (2006) from western Canada, Larocque et al. (2006) from northwestern Québec, and Porinchu et al. (2009a) from southern Victoria Island. At the time this thesis began, no chironomid-based Holocene studies had been published yet for the Canadian Arctic. There are currently three chironomid-based studies spanning the Holocene or longer from Baffin Island (Briner et al., 2006, Francis et al., 2006; Axford et al., 2009a) and one from Southampton Island (Rolland et al., 2008). The three sequences presented here thus greatly increase the available information of past environments in the Arctic. All of these studies look at changes in chironomid species composition to infer past mean July air temperatures for their respective regions.

Thesis research topics

Although paleolimnological studies hold great potential and have generated invaluable information to date regarding past environmental history of a number of regions (and notably for the Arctic, for example see the Western Arctic summary in Kaufman et al. (2004), there remain some important limitations. For example, although studies have interpreted changes through time in sediment proxies such as biogenic silica (BSi) or loss-on-ignition (LOI) as paleoclimate indicators, and in some cases related them to independent paleoclimate records, these inferred relationships have not been tested, validated or quantified in a modern setting. Notably, it remains unclear if the values of these parameters are ultimately related to temperature or other environmental conditions in Arctic lakes. The main objective of Chapter 2 of this thesis is to examine the relationships between sediment parameters of organic, carbonate and BSi content and their environment in a series of lakes across the Canadian Arctic, and to produce inference models from these sediment proxies that could be used to provide quantitative reconstructions of pH and mean July air temperature into the past.

The results of quantitative environmental reconstructions based on a particular proxy such as chironomids are often greatly influenced by the choice of tools and models used in the analysis. The quantitative relations between modern chironomid assemblages and environmental parameters such as July temperature or lake conditions are defined using a geographic series of lakes, a so-called "training set". Current work is based on regional samples of lakes, or training or calibration sets, but decisions such as how to choose the region of study and which lakes to include and which type of inference model to apply are unresolved. Of all chironomid-based training sets available in North America, none were available that contained a large enough number of lakes that appropriately represented past environmental conditions in the Arctic. In Chapter 3 we develop a chironomid-based training set and derive from this training set a transfer function specifically for use in reconstructing mean July air temperatures in the Arctic.

It is important that the lakes selected in the development of the calibration set cover the entire range of the environmental variables of interest. It is also important that the downcore taxa be well represented in this modern calibration set (Arigo et al., 1986)—that there be modern analogues for the fossil assemblages. The rationale in using larger training sets is that they cover larger climatic and environmental gradients and may provide a more complete illustration of the interactions between biological communities and their environments (Birks and Birks, 1980; Lotter et al., 1999, Brooks and Birks, 2001; Whitmore et al., 2005; Viau et al., 2008). As yet, no large-scale study has been conducted in North America for analyzing chironomid-based reconstructions, as current North American chironomid training sets are restricted to one region (Walker et al., 1997; Wilson et al., 2004; Gajewski et al., 2005; Barley et al., 2006; Larocque et al., 2006; Francis et al., 2006; Porinchu et al., 2009a). In Chapter 4 we combine our Arctic chironomid training set (from Chapter 3) with five others from northern North America, and generate a transfer function for estimating mean July air temperatures that can be used for any lake in northern North America.

Paleoecological studies provide a long-term record of environmental change and identify factors that affect ecosystems at long timescales. However, since a paleolimnological study at just one lake is very time consuming to complete, only a few exist for the Arctic region. The strength of paleolimnology arises when comparing a large number of records to better understand what tendencies in the record are local versus regional in nature. Furthermore, using multi-proxy analyses of lake sediment cores, we can study the ecosystem response to environmental change. In Chapters 5, 6 and 7 we study three Arctic lakes: Lake WB02 (Northern Victoria Island; Chapter 5), Lake KR02 (Western Victoria Island; Chapter 6), and Lake JR01 (Boothia Peninsula; Chapter 7). While each have very different environmental contexts, we use the fossil data to infer past environmental conditions at each lake, contextualize the recent warming, and examine changes in lake functioning (production, species composition, interaction between trophic levels) through time. These reconstructions improve our understanding of climatic variations over the Holocene in the Arctic, as well as provide evidence from which to infer the effect of climate change on lower trophic-level organisms in Arctic lakes.

Organization of thesis

I was first author for all publications and chapters in this thesis. Where one chapter cites another within this manuscript, the chapter number cited is in square brackets (e.g., Fortin [2]). Chapter 2 was published in *Polar Biology* (32: 985-998.), Chapter 5 in the *Journal of Paleolimnology* (43: 219-234), Chapter 6 is published in *Quaternary Science Reviews* (27:2090-2110) and Chapter 7 is currently under review at *Quaternary Research* (September 2010).

The order of the chapters in this thesis does not correspond to the order in which they were completed. They are presented here in a logical way such that the methodological chapters are first, which are then followed by chapters discussing the sediment cores. The chronological order of the chapters as they were actually completed is as follows: Chapter 5, Chapter 2, Chapter 6, Chapter 3, Chapter 4, Chapter 7, and Chapter 8. This has unavoidably led to certain inconsistencies in the text; for example, the conclusions developed in Chapter 3 were not used for the core work discussed in Chapters 5 or 6, since these chapters were in fact completed before Chapter 3. Finally, Chapter 8 contains supplementary and new information such as mean July air temperature reconstructions for previously published chapters ([5] and [6]), using methods that were developed afterwards. Extensions used for chironomid taxon names are consistent within each paper but not so between chapters, since different reviewers for the different chapters required different labeling styles for the chironomid taxa. References used in the separate chapters are now combined and placed at the end of the thesis, as are the appendices containing the raw data for each chapter.

Chapter 2

Assessing the use of sediment organic, carbonate and biogenic silica content as indicators of environmental conditions in Arctic lakes

Marie-Claude Fortin*, Konrad Gajewski

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Abstract

The objective of this paper is to examine three sediment parameters used in paleolimnological studies, sediment organic, carbonate and biogenic silica (BSi) content, and to quantify the relationship among these parameters and modern environmental conditions for a series of Canadian Arctic lakes. Sediment samples from 63 lakes were analysed for organic, carbonate and BSi content. The environmental and physical parameters of these lakes were recorded. Bedrock composition exerted a very strong influence on sediment organic, BSi and carbonate content, and differences in lake production accounted for much of the remaining variance. The strongest relationships existed among sediment carbonate content, BSi content and water pH. A statistical model developed for predicting water pH provides a new tool for reconstructing past environmental conditions for Arctic aquatic ecosystems. A positive relationship between mean July air temperature and sediment organic and BSi content was detected, but was confounded by effects of bedrock on these parameters. However, the relationship between mean July air temperature and sediment organic and BSi could be even more significant in the context of constant bedrock composition, as is the case in paleolimnological studies.

Introduction

Fossil organisms preserved in lake sediment cores can be used to infer past climatic and limnological conditions (Birks and Birks, 1980). Analysis of other parameters of the sediment matrix, such as sediment organic content, also provides insight into past environments. In microfossil based paleolimnological studies, quantification of environmental variables is based on a two-step process. First, the modern-day relationship between the fossilized organisms and their environment is quantified using a spatial series of sites. Then, the statistical model derived from this process is applied to the downcore fossil data to produce the reconstruction of an environmental variable through time (Birks and Birks, 1980). Qualitative analyses of other sediment parameters can then be used to substantiate the quantitative interpretation of lake environmental history.

A fundamental limitation associated with fossil-based inference techniques is the time required to extract and identify the fossils; this results in many records generating low temporal resolution reconstructions. Errors in parameter estimation and ambiguity in determining the factors that affect the organism can lead to relatively large error bars in the reconstructions. The presence of non-analogue fossil communities, those with no modern equivalents, adds further complexity to the interpretation of fossil-based paleoenvironmental studies. One mechanism for determining the reliability of the paleoclimate reconstructions is to use several proxy records as checks on each other.

The issues with the use of organism-based methods have led to the use of other approaches to paleoenvironmental analysis, including physical and chemical analyses of the bulk sediment. Among these approaches, there has been an interest in using simple parameters such as sediment organic, carbonate and biogenic silica (BSi) content as paleoenvironmental proxy records (e.g. Levesque et al., 1993; Colman et al., 1995; Willemse and Törnqvist, 1999; Conley and Schelske, 2001; Kaplan et al., 2002; Hu et al., 2003; Andresen et al., 2004; 2006; McKay et al., 2008). These parameters are relatively quickly measured and require only small sediment sample size, allowing high sampling resolution. Using the information generated by these sediment parameters in conjunction with that derived fossil data provides a more complete representation of past environments.

Organic matter preserved in lacustrine sediments comprises both allochthonous material washed in from the landscape and autochthonous biomass, produced within the lake, that settles onto the lake floor (Kalff, 2001). It is composed of the remains of past biota living in and around the lake. Since the production and biodiversity of the biota is associated with the physical environment, including the climate, changes in lake sediment organic concentrations have been associated with changes in climatic and other environmental variables (e.g. Willemse and Törnqvist, 1999). Another source of carbon in lake sediments is inorganic carbon in the form of carbonate derived from bedrock through weathering. Carbonate can also be directly precipitated from the water column through both organic and inorganic mechanisms (Kalff, 2001).

Biogenic silica represents the amorphous fraction of silica found in the sediment matrix of biological origin. It originates from siliceous organisms such as diatoms, sponge spicules and chrysophytes that lived in the water column and on the lake floor. BSi has been used as a proxy for diatom abundance and aquatic primary production (Conley, 1988).

One common interpretation is to use sediment organic content as an index of past temperature. This is based on a number of paleolimnological studies that have noted a synchronicity through time between changes in these parameters and climatic changes. For example, Willemse and Törnqvist (1999) found synchronous changes in lacustrine sediment organic content records from six West Greenland lakes. The variations in organic matter paralleled air temperature (AT) fluctuations as interpreted from the Greenland Ice core $\delta^{18}O$ record. Kaplan et al. (2002) also found a strong linkage between lake sediment organic and BSi content and AT during the Holocene in southern Greenland. Hu et al. (2003) recognized that the cyclicity present in the sediment BSi record from their study lake in Alaska was generally consistent with variations in solar activity, which presumably affected the climate. Subsequently, McKay et al. (2008) quantified the temperature variations through time in one site by relating BSi time series spanning the past 125 years in a sediment core to nearby meteorological records.

A number of studies now directly interpret sediment organic and BSi content downcore as measures of whole system and primary production as well as a reflection, directly or indirectly, of past climatic conditions. For example, in a recent paleoclimate compilation of studies of Arctic lake sediments of the past 2,000 years (Kaufman et al., 2009), sediment organic and BSi content were the most common proxies used (e.g. Axford et al., 2009b; Chipman et al., 2009; Geirsdòttir et al., 2009; MacDonald et al., 2009; McKay and Kaufman, 2009; Peros and Gajewski, 2009; Porinchu et al., 2009a; Thomas and Briner, 2009). Although the above studies have inferred relationships between sediment proxies and environmental conditions, and in some cases related them to independent paleoclimate records, these inferred relationships have not been tested, validated or quantified in a modern setting. Notably, it remains unclear if the values of these parameters are ultimately related to temperature or other environmental conditions in Arctic lakes.

The purpose of this paper is to examine the relationships between sediment parameters of organic, carbonate and BSi content and their environment in a series of lakes across the Canadian Arctic. The primary focus will be on examining the geographical patterns of these sediment parameters in a series of Arctic lakes and determining the limnological and geological factors that most strongly affect their concentrations in lacustrine sediments. As a secondary focus, we will examine the possibility of using the relationships between the parameters and their environment to produce inference models from these sediment proxies that could be used to provide quantitative reconstructions of pH and AT in the past. The limitations associated with such models will also be discussed.

Methods

Field

Surface sediments were collected from the central part of 63 lakes across the Canadian Arctic using either a Livingston piston corer or Glew surface corer (Fig. 1). Lakes were sampled at various times in early to midsummer from 1990 to 2007. A few of the lakes used in this study were included in previous studies, documenting the modern biogeography of diatoms (Bouchard et al., 2004) and chironomids (Gajewski et al., 2005) in the Canadian Arctic, and the limnology of some was summarized in Hamilton et al. (2001). Lake water was sampled and environmental parameters and lake depth were recorded at each site. Lake water pH and conductivity were measured in the field using hand-held meters. Water samples were collected and preserved using Environment Canada (1994) protocols, and returned to the laboratory for further analysis.

Laboratory

The concentration of nutrients, micronutrients, forms of carbon and major ions in the water were measured in Environment Canada (Burlington) or City of Ottawa laboratories. Chlorophyll *a* (Chl *a*) concentrations of the lake water, uncorrected for phaeopigments, were estimated using standard Environment Canada protocols (1994).

Sediment organic matter (LOI550) and carbonate content (LOI950) were estimated using a loss-on-ignition method through successive heating of the sediment at 550 and 950°C in a furnace (Dean, 1974; Heiri et al., 2001). Within-batch and between-batch replicates of samples were used to assess experimental error.

Biogenic silica extraction was performed on all sediment samples using a wet-alkaline digestion technique. All samples were digested with a weak base (1% Na_2CO_3), subsampled after 2, 3, 4 and 5 h, further reduced using molybdosilic acid and finally analysed through spectophotometry (DeMaster, 1981; Parsons et al., 1984; Conley, 1998; Conley and Schelske, 2001). To ensure internal experimental control, duplicate samples of known BSi content, provided by an interlaboratory study, were used for each extraction batch (Conley, 1998). For all batches, the reference samples were consistently within one standard deviation of their mean BSi weight percentage value provided by the study.

Although sediment organic, carbonate and BSi content are all percentage values taken from the same volume, they are not the only components of the sediment and their sums do not equal 100%. As such, an increase in one does not necessarily cause a decrease in another. Therefore, a quantifiable inverse relationship between these parameters is not necessarily a statistical artefact, but rather the result of an environmental process (Dean, 1999).

The bedrock composition surrounding each lake was extracted from Geological Survey of Canada maps 1715A and 1860A (Okulitch, 1991) and vegetation from the Circumpolar Arctic Vegetation Map (Wheeler et al., 1997, CAVM Team, 2003). Although there are a small number of discrepancies between vegetation complexes identified by the CAVM maps and our personal observations made during field work, the CAVM classifications were retained for consistency. Mean July AT for each site was extracted from the data files of Atkinson and Gajewski (2002). Lake area and distance from coast (DFC) were verified using Google Earth and topographic maps.

It is a general practice to collect sediment for analysis from the deepest and most central location within a lake. We wanted to quantify the variability in lake sediment organic, carbonate and BSi content found within these specific locations. From the original 63 lakes, a subgroup of five lakes was cored at three central sites within each lake. For this subgroup, replicate surface sediment samples at these three sites were analysed for organic, carbonate and BSi content. Depending on sediment availability, three or four replicates per site were analysed.

Numerical analysis

Only environmental and chemical variables with fewer than six missing values (<10% of the total number of lakes) and having fewer than 50% of their values below detection levels were included in the analysis. Missing values were replaced by the mean for that variable and values below detection levels were replaced by the mid-point between the detection level and zero. Based on the results of an exploratory data analysis, biogenic silica weight% (BSi), DFC, lake area, conductivity (CON), dissolved organic carbon (DOC), total Kjeldahl nitrogen (TKN), total phosphorus unfiltered (TP), Cl^- and SO_4^{2-} were log transformed, organic (as measured by loss on ignition at 550°C) and carbonate (as measured by loss on ignition at 950°C) weight%, SiO_2, Chl *a*, Fe^{2+}, K^+, Mg^{2+} and Na^+ were square root transformed and mean July AT, latitude (lat), longitude (lon), elevation and pH remained untransformed prior to data analysis.

To understand the source of the variability in organic, carbonate and BSi content, a two-factor nested analysis of variance (also known as hierarchical ANOVA) was performed for each of the variables (Sokal and Rohlf, 1981). This ANOVA examined the within-lake and between-lake variation of these parameters and also the analytical error involved in using the loss-on-ignition and the wet-alkaline digestion technique. For this portion of the study, surface sediment was sampled in five lakes: one lake from Melville Island (lake 1), Ellesmere Island (lake 2) and Devon Island (lake 3) and two from southern Boothia Peninsula (lakes 4 and 5). In each of these five lakes, triplicate samples (and in some instances, quadruplicate) from three central locations in each lake were analysed for sediment organic, carbonate and BSi content. As sample sizes were sometimes unequal, a Satterthwaite's approximation was used to correct for this unbalance in the analysis. The triplicate (quadruplicate) samples were all taken from the same original core and are therefore used to examine the analytical error involved in using the loss-on-ignition and the wet-alkaline digestion technique rather than within-location variability.

A principal components analysis (PCA) was performed on the transformed data to examine the relationship between environmental variables and sediment organic, carbonate and BSi contents. Relationships between pH and mean July AT with sediment organic and BSi content were then calibrated through the use of simple and multiple linear regression. Finally, linear models were developed for calculating pH and mean July AT from a combination of the sediment organic, carbonate and BSi variables.

Results

Limnology of the study sites

The lakes in the training set spanned five of the six geological provinces of the Canadian Arctic (excluding the Arctic Continental Shelf). The lakes were all oligotrophic to weakly mesotrophic and generally nutrient poor (mean TP unfiltered = 0.3 μmol L^{-1} (0.01 mg L^{-1}), mean TKN = 12.9 μmol L^{-1} (0.18 mg L^{-1}), Table 1). DOC was generally very low (mean DOC = 169 μmol L^{-1} (2.0 mg C L^{-1})) and lake water Chl *a* concentrations were often below detection levels. However, many of the lakes were sampled very early in the ice-free season, so the Chl *a* measurements probably underestimate the actual productivity of the lakes; in addition, these measurements only record lake water, and not benthic productivity. The conductivity of the lake water varied over four orders of magnitude; however, only four lakes had conductivities larger than 300 μS cm^{-1}. As in most studies conducted on Arctic lakes, the cation concentrations were ranked Ca^{2+}>Mg^{2+}>Na^{+}>K^{+}. High concentrations of Ca^{2+} and Mg^{2+} are common in lakes located on limestone and dolostone bedrock; half of the lakes included in this study are located on carbonate or carbonate–quartz bedrock. The pH values ranged from 6.0 to 8.6 (mean = 7.6) and were on average highest for the lakes located on carbonate bedrock. Lakes on other types of sedimentary substrates (quartz, coal and evaporitic) as well as those on mafic intrusive and gneiss bedrocks ranged in pH from 6.0 to 8.3. Although particulate organic carbon (POC) concentrations were not further analysed in this study, as they were only measured for a subset of the lakes (n = 26), the POC:Chl *a* ratios for this subset of lakes ranged from 6 to 6,180 (mean = 1,382). Only five lakes had ratios below 100 and all were located in a small area of northern Victoria Island. The POC:Chl *a* ratio of the lakes therefore suggests that a large part of the organic carbon in the lake water is derived from terrestrial sources (Eppley et al., 1977).

Sediment organic content (as measure by loss on ignition) varied greatly among lakes (0.2–48.0 weight%, mean = 13.5 weight%) and provided a range of sites with values along the entire gradient. Sediment BSi was generally much lower (2.5–12.0 weight%, mean = 2.5 weight%). The range and mean sediment carbonate content values were similar to those of the sediment organic content (ranging from 8.5 to 33.2 weight%, mean = 8.5 weight%).

Organic and BSi sediment concentrations were low in lakes located on carbonate bedrock (mean organic = 9.6 weight%, mean BSi = 1.2 weight%). Lakes on gneiss/mafic intrusive bedrocks had low organic content, but higher sediment BSi content (mean organic = 7.8 weight% and mean BSi = 3.5 weight%). Lakes on coal/evaporitic/quartz sedimentary rock had the highest organic content (mean organic = 18.7 weight% and mean BSi = 3.2 weight%). Sediment carbonate content was, not surprisingly, highest in lakes located on carbonate bedrock (mean carbonate = 15.8 weight%) and lowest on bedrock composed of mafic intrusive rocks, gneiss and evaporitic, coal and quartz sedimentary rocks (average mean sediment carbonate content for these bedrocks = 3.4 weight%).

Sediment organic and BSi content followed similar geographical patterns. Organic content was highest in the Fosheim Peninsula, Victoria Island and southern Boothia Peninsula (Figure 2). Sediment BSi was also highest in lakes located in the Fosheim region, as well as on Melville Island and the most southern sampling locations on the Boothia Peninsula. Map patterns show opposite relationships between BSi sediment content and both carbonate content and lake water pH. Both sediment organic and biogenic concentrations were lowest in the central region, including Bathurst, Cornwallis, Devon, Prince of Wales and Somerset Islands. The highest carbonate content was in the sediment of lakes on Devon Island and northern Victoria Island.

Lakes located on the Boothia Peninsula and on western Victoria Island experience warmer July ATs, had higher nutrient concentrations and were generally surrounded by denser vegetation. To the north, in the middle and high Arctic zones, July temperatures were cooler and lake water TKN, TP and DOC decreased. Lakes on Devon Island generally experienced cooler July ATs and had much lower concentrations of nutrients than at any other sites. The mesoclimate surrounding the lakes located on the Fosheim Peninsula region of Ellesmere Island leads to the anomalously warm mean July ATs (Garneau and Alt, 2000), high lake water nutrient and DOC concentrations for this latitude. Overall, lakes on gneiss/mafic intrusive and coal/evaporitic/quartz sedimentary bedrocks had higher nutrient concentrations (TP and TKN) and DOC than those on carbonitic bedrock.

Within-lake variability

A nested analysis of variance used to examine the within- and between-lake differences in organic, carbonate and BSi sediment content produced similar results for all three of these parameters (Table 2). In all cases, the between-sample variance within each lake was significantly larger than the within-replicate variance at each site. In all lakes but one, the deepest site within each lake had significantly higher organic concentrations than the shallowest site; the opposite was true for sediment carbonate concentrations. The between-lake variance was larger than the between-sample variance within the lakes (Figure 3). The necessary corrections made to the ANOVAs due to an unbalanced sample design did not significantly affect any of the resulting statistics.

Exploratory data analysis

A principal components analysis was performed on the transformed data to examine the multivariate relationships between lake and watershed properties and sediment organic, BSi and carbonate content. The first two components explained 35 and 14% of the total variance (Figure 4a). Major ions, conductivity, SiO_2 and SO_4^{2-} were positively loaded on the first component. BSi and organic content of the sediment, and TP of the water were highly negatively loaded on the second component, whereas sediment carbonate content and lake water pH were positively loaded on this component. Mean July AT, DOC and TKN were highly loaded on both the first and second axes (positively and negatively, respectively) as was lake surface area (negatively on the first and positively the second). Fe and Chl *a* were both positively loaded on the third component (not shown).

Lakes with similar vegetation types generally clustered together on the biplot (Figure 4b). Lakes located in ''barrens'' vegetation (i.e., polar desert; CAVM, Team, 2003) were typically located in the upper half of the ordination biplot, where carbonate sediment concentrations were highest, and sediment BSi and organic matter were lowest. Lakes surrounded by the most dense and diverse vegetation (prostrate dwarf shrub) tended to ordinate on the right side of the plot, where lake waters have highest nutrients.

Lakes on bedrock comprising clastic and chemical sedimentary rocks contained quartz, coal and evaporites and ordinated negatively on the second axis, whereas lakes on quartz–carbonate and carbonate–bedrock ordinated positively on the second axis (Figure 4c). Lakes on gneiss were negatively loaded on both axes, whereas lakes on mafic intrusive bedrock did not have high loadings on either axis (Figure 4c); however, there were few lakes in these categories.

A simple pairwise correlation analysis comparing sediment parameters with the environmental variables substantiated the results of the PCA. The correlation analysis established that the strongest relationships with sediment BSi content were pH, DFC (r = -0.38, 0.38, respectively; $p<0.001$), conductivity, mean July AT and Chl *a* (r = -0.20, 0.20, -0.20, respectively; $p<0.12$). The strongest relationships between sediment organic content were with lake surface area, SiO2, SO4 2- (r = -0.44, 0.40, 0.37, respectively; $p<0.001$), Ca^{2+}, K^{+}, Mg^{2+}, DOC (r = 0.27, 0.27, 0.26, 0.26, respectively; $p<0.05$) and with sediment carbonate content were pH, Ca^{2+}, Mg^{2+} (r = 0.44, 0.31, 0.27, respectively; $p<0.001$) and Fe^{2+} (r = -0.27; $p<0.05$). Sediment organic matter was positively correlated with BSi sediment content (r = 0.52, p<0.001) and uncorrelated with sediment carbonate content. Sediment BSi and carbonate content were negatively correlated (r = -0.29, p<0.01).

Calibration models

One of the goals of this paper was to determine if sediment parameters could be used to reconstruct environmental variables, such as AT, in the past using measurements made at depth in sediment cores. In order to accomplish this, suitable regression equations would need to be established using modern data.

The correlation analysis presented above, as well as the PCA, determined that lake water pH was one of the environmental variables that was most strongly related to a combination of sediment organic, carbonate and BSi content. Furthermore, since the PCA indicated a relationship among mean July AT and the sediment parameters, we explored the possibility of using these parameters to calibrate past ATs. In addition, this exercise was undertaken because understanding temperature changes through time remains a major goal of many paleoenvironmental studies. However, it proved impossible to develop a suitable regression model of temperature and these variables, although weak univariate relationships were present between mean July AT and BSi (r = 0.202, p = 0.12) and mean July AT and organic content (r = 0.18, p = 0.166; Fig. 5a). The best possible model for mean July AT was significant only at a 77% confidence interval. Although the range of the residuals exceeded that of the fitted values, the residuals of this model did not otherwise exhibit trends when plotted against fitted values or indicate violations of the assumptions of the regression model. However, when predicted AT versus observed AT values were plotted, poor results were indicated (not shown).

A weak, but significant, correlation existed between lake water pH and sediment carbonate content ($r = 0.447$, $p = 0.0002$) and lake water pH and sediment BSi ($r = -0.38$, $p = 0.002$) (Fig. 5b). A multiple regression analysis provided the following model to calculate pH from these parameters:

$$pH = 7.26 + 0.16 * \sqrt{(\%carbonate)} - 0.18 * \log(\%BSi)$$

$$(r^2=0.51, p=1 * 10^{-4}).$$

There were no distinguishable patterns when the normally distributed residuals from this model were plotted against the fitted values. Similarly, no significant outliers were detected, suggesting that the model does not violate the assumptions of the regression method. Although residuals indicate no significant problem, predicted pH is overestimated at low pH values (Figure 6).

Discussion

Within-lake variability

The results of the ANOVA indicate that the analytical error involved in using the loss-on-ignition and the wet-alkaline digestion technique were not significant contributors to the overall variance of sediment organic, carbonate and BSi content, and therefore the extraction or measurement well characterizes the point sample. The three sampling sites within the lake basins recorded different values of these sediment parameters, although the significance of these differences is difficult to assess due to pseudo-replication of the within-site samples. Sediment organic, carbonate and BSi content can vary across a lake basin due to the differential distribution of the sediment throughout the lake, a process also known as sediment focusing (Håkanson and Jansson, 1983). Nevertheless, in spite of differences across the lake basin, the nested ANOVA confirmed that there were significant differences in organic, carbonate and BSi content among lakes across the Arctic, that is, the spatial variability remains greater than the within-lake variability. This suggests that environmental factors such as temperature, bedrock, surrounding vegetation and lake water properties have significant impacts on these indices.

These results are based on single-point measurements that are used to represent conditions of the lake, a common practice in paleolimnological studies. Although this is generally acknowledged to be a potential issue, Bunbury and Gajewski (2008) have empirically suggested that this practice may be warranted when making comparisons among lakes.

Between-lake variability

The principal components analysis indicates that 50% of the variance in these data can be explained by two gradients, which are both strongly related to bedrock composition. Lake water ionic composition as well as DOC concentrations account for a large portion of the variance in the limnological and environmental data of our lakes. The ionic composition of lake water reflects the mineralogy of the underlying bedrock (Wetzel, 2001). Lakes from this study on carbonitic bedrock had higher Ca^{2+} and SO_4^{2-} concentrations, whereas sites on readily soluble evaporites had increased Na^+ and Cl^- composition, confirming the importance of bedrock weathering in the ionic composition of the lakes. Furthermore, lakes cluster on the biplot primarily according to bedrock type and to their relationship with sediment carbonate content. Factors associated with bedrock composition therefore account for the primary source of variance among these sites.

The sediment parameters (organic, carbonate and BSi content) as well as TP and TKN also account for an important, although smaller, proportion of the overall variance. The nutrients TP and TKN are often used as indicators of lacustrine production, especially in an Arctic setting, where both P and N derivatives have been documented as limiting factors in aquatic primary production (Kalff, 1971; Prentki et al., 1980; Alexander et al., 1989; Wetzel, 2001). Nitrogen compounds can be fixed in situ in lake sediments and recycled through the water column; however, in Arctic lakes, both N and P compounds are mostly derived from allochthonous material washed in from the landscape or leached from the surrounding bedrock (Alexander et al., 1989; Kalff, 2001). The close ordination of TKN and TP with DOC, which is predominantly terrestrial in origin in Arctic lakes (see POC:Chl *a* ratio) (Hamilton et al., 2001) may further support the argument that lake water TKN and TP are allochthonous in nature. Temperature is also positively related with nutrients in these sites. The secondary source of variance in these lakes is therefore explained by the gradient of lacustrine and watershed productivity, and this is broadly associated with the climate.

There was no correlation between water Chl *a* concentrations and either sediment organic or BSi content, and the spatial pattern of Chl *a* bears no similarity with either of these variables or with any nutrients (not shown). This lack of relationship has been observed in a large number of Arctic paleolimnological studies (e.g. Hamilton et al., 2001; Lim et al., 2001; Michelutti et al., 2002a; b), leading Hamilton et al. (2001) to conclude that Chl *a* is a poor indicator of trophic status of very unproductive lakes.

Rowan et al. (1992) and our study found a strong inverse relationship between lake surface area and lake sediment organic content. The larger lakes in our calibration set all had lower values of organic content and, to a lesser extent, BSi content. They also had the lowest concentrations of major elements, such as TP, TKN, K^+ and DOC. One explanation for this observation is that larger and deeper lakes would have a shorter growing season when compared to smaller lakes, due to the delay in ice melt at their surface resulting from the thermal inertia experienced by larger lakes (Wetzel, 2001). Another explanation is simply that organic and BSi production is diluted in the larger lakes and that the nutrients washed in from the watershed, such as TP and TKN that are required for this production, are likewise diluted (Hamilton et al., 2001; Lim et al., 2001). The generally low concentrations of nutrients, micronutrients, forms of carbon and certain major ions corroborate both these explanations. The effect of lake depth on the sediment and water chemical parameters therefore needs to be fully considered when making comparisons among lakes, but might otherwise be negligible when examining the fossil record of a single lake.

Relationship among sediment parameters and environmental variables

Bedrock composition exerts a strong influence on sediment organic, BSi and carbonate composition in these Arctic lakes. In this study, the primary production and nutrient content of the lakes located on carbonate bedrock are both quite low, especially when compared to lakes on other substrates. The sediment carbonate content in these lakes remains high, as the bedrock itself is predominantly composed of carbonitic material. A potential explanation for the low production of Arctic hard-water lakes is that the small amount of P and marginally larger amounts of N compounds washed in from the polar desert landscape that surround these lakes are quickly precipitated from the water column due to the calcareous nature of the bedrock and remain unavailable to primary producers (Wetzel, 2001).

Although lakes on igneous and metamorphic bedrock appear to have higher diatom production, overall these lakes are not significantly more productive than the ones on carbonate bedrocks. These types of bedrock often contain low concentrations of N and P and are more difficult to erode than sedimentary rock. Although no clear distinction is apparent in the concentration of sediment organic and BSi content between detrital and evaporitic sedimentary bedrock, both these types of bedrock underlay lakes that are more productive than the lakes on the calcareous or gneiss and mafic intrusive bedrock. The simple pairwise correlations also indicate that sediment organic, BSi and carbonate content were significantly related either to the concentrations of the major ions in the water column or to lake water pH or both, which again confirms the influence of bedrock composition on these lacustrine sediment parameters.

Lake water pH was identified as one of the environmental variables that could potentially be modeled using sediment parameters. Lake water pH is affected by a number of factors, including catchment vegetation type and abundance, lake bedrock composition (namely the acid buffering capabilities of the lacustrine sediment), seasonality (for example, ice cover versus open water), edaphic input of dust and particles and within-lake rates of photosynthesis, respiration and organic matter decomposition (Psenner and Schmidt, 1992; Kalff, 2001; Wolfe, 2002). From the results of the exploratory and regression analysis, it was determined that lake water pH was significantly correlated with sediment BSi and carbonate content. Sites with high pH values generally had high carbonate, but low BSi content in the sediment.

Lake carbonate content is predominantly controlled by lake bedrock composition, with higher sediment carbonate content for lakes on carbonate bedrock. The carbonate content in lake sediment acts as a buffer against large changes in lake water pH; lakes with higher carbonate content are less susceptible to the pressures that biological and environmental processes may exert on lake water pH. In these hard-water lakes, an equilibrium is maintained between water and sediment forms of inorganic carbon through the dissolution and precipitation of carbonates in the sediment. As a result, carbonate-rich lakes tend to maintain a circumneutral to alkaline lake water pH. Lakes on substrates with very low concentrations of carbonates such as igneous or metamorphic bedrocks are more susceptible to becoming more acidic under changing environmental pressures, as they have limited buffering capability. These lakes tend to have a wider range of pH values, including a larger number of lakes with pH in the acidic range.

Lake water pH is also significantly negatively correlated with sediment BSi content. Sediment BSi content is influenced by a large number of factors such as climatic conditions, nutrient availability and other lake water parameters. In a number of down-core studies, a positive relationship has been described between diatom concentrations (for which BSi can be used as a proxy) and lake water pH (e.g. Psenner and Schmidt, 1992; Wolfe, 2002; Michelutti et al., 2006). However, this relationship is opposite to that found in our study. The aforementioned studies suggest that the observed increase in lacustrine diatom productivity causes, through increased photosynthetic activity, a decrease in limnetic CO_2. This decrease in CO_2 results in the increase in water pH which, in these studies, was inferred from the diatom record. Similarly to other circumpolar Arctic studies, increases in diatom production or BSi are generally linked to more favourable climatic conditions (Kaplan et al., 2002; Hu et al., 2003; McKay et al., 2008). However, a number of these authors do caution that this reasoning may only be applicable to their specific study lakes, and that substrate composition and other environmental factors may alter the nature of the relationship between lake water pH and BSi.

There are a few possible mechanisms explaining the negative relationship observed in this study between lake sediment BSi and lake water pH. The first is that an increase in BSi content could in fact lead to an increase in limnetic CO_2 and thus a decrease in pH. In this scenario, increased sediment BSi content, which corresponds to higher production of diatoms, would allow a larger pool of primary and higher-order consumers to be sustained. This would in turn increase the amount of CO_2 released into the water through consumer respiration. In fact, Hobbie (1984) found that in tundra ponds, the respiration can become so great that the water above becomes supersaturated with CO_2, in turn decreasing the water pH. Psenner and Schmidt (1992) also note that an increase in lacustrine organic matter concentration (which includes sediment BSi content) could in turn increase organic decomposition, possibly generating enough CO_2 to counteract the removal of CO_2 from the water column by algal photosynthesis. Increased consumer respiration and organic decomposition could, coupled together, cause a decrease in lake water pH when diatom production and therefore sediment BSi content increases. Although this scenario is possible under very specific conditions, it is improbable that this explanation corresponds to what is occurring in the great majority of these unproductive study lakes.

Conversely, it is possible that lake water pH influences sediment BSi content. Diatom communities may be more productive and/or better preserved in more acidic environments and less productive under more alkaline conditions. The more alkaline lakes in this study are generally located on carbonate bedrocks surrounded by polar deserts and are associated with lower water nutrient content and cooler climatic conditions. Under these conditions, it is not surprising that diatom production and therefore sediment BSi content is lower than in lakes surrounded by denser vegetation and containing greater nutrients, as is the case of a great number of lakes on other types of sedimentary bedrocks. Further evidence supporting the influence of pH on sediment BSi content is that the silicious valves of diatoms tend to dissolve under increasingly basic conditions. In fact, Flower (1993), Barker et al. (1994) and Ryves et al. (2006) all demonstrated that lake water pH is a significant factor affecting the preservation of diatoms. The dissolution of diatom silicious walls in alkaline conditions can occur at pH as low as 7 (Flower, 1993) and exponential decay occurs from a pH of 9 (Barker et al., 1994). Hurd (1983) states that a decrease of half a pH unit would result in the reduction of silica dissolution rates by half. Arctic lakes with both higher and lower pH can still contain well-preserved diatoms; however, from paleolimnological studies, there is mounting evidence that dissolution and diatom fragmentation may have occurred in circumneutral to alkaline Arctic lakes and that this dissolution is in part due to changes in lake chemical properties such as pH (Finklestein and Gajewski, 2007; Podritske and Gajewski, 2007; Fortin and Gajewski, 2010a [5]). However, it remains unclear if dissolution occurs only beyond a certain threshold pH (for example, 7 as stated by Flower in 1993) or if lake water pH has a more linear effect on the preservation of diatom valves and this across a broader range of pHs. In either case, it is likely that bedrock composition, which affects lake water pH, influences sediment BSi concentration.

A model for reconstructing lake water pH from sediment carbonate and BSi content was developed. This model is preliminary, as it is based on only 63 sites. This model is statistically significant, but only accounts for a small portion of overall variance in lake water pH and provides reasonable predictions only when the pH is above 7. However, certain limitations significantly affect the general applicability of this model. The series of lakes used to develop this model are located on a number of different substrates and may therefore not include enough of the variability that exists for each substrate; in particular, we had few lakes with low pH. Furthermore, until processes such as diatom dissolution are better understood, it is difficult to determine if this pH reconstruction model can be applied to any lake or if the effect of dissolution on individual lakes needs to be considered (see Ryves et al., 2008).

The results from this study also indicate that there may exist noteworthy relationships between mean July AT and sediment organic and BSi content in this array of modern sediments, although we are unable to develop a reasonable calibration model using these sediment parameters. The ordination diagram clearly shows that in the context of overall lake functioning, there is a relationship among mean July AT, and sediment organic and BSi content. The overall similarities in the geographical patterns of sediment organic and BSi content, mean July AT and TKN (as well as TP, not shown) across the Arctic further suggest a positive relationship among AT, nutrient availability and aquatic production.

There are a number of potential mechanisms explaining the effect of AT on lake production. Warmer conditions leading to greater snow melt could result in a higher rate of surface runoff from the surrounding watershed into the lake, thereby increasing the concentrations of organic matter and nutrients washed in from the surrounding vegetation and bedrock (Brodersen and Quinlan, 2006). These nutrients and organic compounds are then available to primary producers and these two sources generate higher organic matter and BSi in the sediments. Warmer ATs can also lead to decreased ice cover and a longer summer growing period in lakes, which would encourage the growth of primary producers and overall organic matter export to the sediment (Smol, 1983). In warmer conditions, metabolic processes within the water column such as nutrient recycling and species turnover rates are accelerated, contributing to higher organic production in these lakes. In fact, the warmer sites in this study also correspond to more densely vegetated watersheds. Therefore, lakes located in warmer areas could receive larger contributions of terrestrial organic matter to their sediments, which in turn contributes to the higher sediment organic content of these lakes.

The weak results of the regression analysis may be due to a number of factors. Data collection, which occurred at different moments in the growing season and over a 17-year period may have significantly contributed to the large variance in the data. As such, a focused field campaign may be beneficial. The effect of temperature on lake production may in fact be indirect, as discussed above, and therefore not easily quantifiable through simple regression analysis. In addition, edaphic factors, most notably bedrock composition, may differentially influence how AT affects lake production (Michelutti et al., 2006). The influence of substrate type on the sediment parameters appears to be so important that it may in fact be masking any potential relationship between AT and sediment organic, BSi and carbonate content. To pursue this idea, an analysis similar to the one conducted in this study should be performed, but this time using a much greater sample size of lakes from each of the different types of bedrock. This would allow for a more complete statistical analysis of the relationships among environment parameters and sediment parameters within the framework of each different type of substrate. Subsequent comparative analyses could then be performed between substrate types and environmental reconstruction models generated for each substrate type.

In paleoenvironmental studies, whose goal is the analysis of environmental change at a single site through time, the influence of bedrock on the sediment organic and BSi content as identified in this study may not be a significant factor, leaving AT as an important influence on these parameters. In fact, a number of Arctic paleoenvironmental studies, such as Kaplan et al. (2002), Andresen et al. (2004), McKay et al. (2008) and Fortin and Gajewski (2010a [5]), have proposed positive relationships among sediment organic content, BSi content (or both) and inferred ATs through the Holocene. This implies that the influences of mean July AT and nutrient inputs could, in fact, be responsible for higher-frequency variability in sediment organic and BSi content in the context of paleolimnological studies, although independent estimates of ATs are needed to confirm these relationships.

Conclusion

This study examined the relationships among lacustrine sediment organic, carbonate and BSi content and lake environmental conditions across the Canadian Arctic. Bedrock composition was the main environmental factor affecting sediment organic, carbonate and BSi content. The concentrations of these parameters in the sediment were also affected by lake trophic status. A significant relationship existed between lake water pH and sediment carbonate and BSi content. The model generated in this study for predicting lake water pH provides a tool to derive past environmental conditions in the Arctic from lacustrine sediment cores. Although it is not possible at this point to quantitatively reconstruct mean July AT from sediment organic and BSi content, the results from this study indicate that there may still exist noteworthy relationships between these parameters. These relationships are furthermore significant in the context of paleolimnological studies where bedrock composition remains relatively constant through time.

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Table 1 Summary of the major environmental, physical and chemical parameters of 63 Canadian Arctic lakes (Figure 1) (SI units)

Variable	Mean	Median	Minimum	Maximum	SD	Units
Biogenic silica (sediment)	2 5	1 7	0 2	12 0	2 7	weight %
Organic (sediment)	13 5	9 1	0 2	48 0	11 4	weight %
Carbonate (sediment)	8 5	6 0	0 1	33 2	8 4	weight %
Conductivity	117 6	65 0	2 5	1003 6	165 2	µS cm^{1}
pH	7 6	7 8	6 1	8 6	0 6	
Disolved Organic Carbon	169 0	141 5	20 8	1124 1	186 5	µmol L^{1}
Total Kjeldahl Nitrogen	12 9	10 0	0 7	78 5	14 3	µmol L^{1}
Total Phosphorus unfiltered	0 3	0 3	0 1	2 3	0 4	µmol L^{1}
Ca	503 0	374 3	2 0	3493 2	578 9	µmol L^{1}
Cl	110 0	35 8	1 4	3201 4	411 8	µmol L^{1}
Fe	1 1	0 5	0 02	19 0	1 8	µmol L^{1}
K	18 4	7 7	0 03	249 1	38 4	µmol L^{1}
Mg	213 5	160 5	0 4	892 8	230 4	µmol L^{1}
Na	216 6	30 4	1 7	4365 4	709 0	µmol L^{1}
Silica	21 0	16 7	0 1	80 1	21 4	µmol L^{1}
Sulphate	185 5	22 9	0 5	4112 8	567 5	µmol L^{1}
Chlorophyll *a* uncorrected	0 5	0 5	0 1	1 6	0 4	µg L^{1}
Mean July Air Temperature	5 7	5 7	2 9	7 3	1 1	°C
Latitude	74 42	74 68	68 57	80 83	4	d d
Longitude	96 77	94 92	82 54	113 97	10 6	d d
Distance from coast	22	15	1	62	20	km
Elevation	215	190	1	855	134	m
Coring depth	7 8	5 6	0 6	34	6 5	m
Surface area	0 49	0 16	0 01	8 16	1 20	km^{2}

Table 2 Two-factor nested analysis of variance summary table for sediment biogenic silica, organic and carbonate content (weight %), see text for details

Source of variation	*df*	SS	MS	Fs	*F*'s	Fcrit $p < 10^{-3}$
BSi						
Between lakes	4	970.6	242.6	6.13	6.08	5.99
Between samples	10	396.0	39.6	17.62		3.90
Within replicates	39	87.7	2.2			
Total	53	1,454.3				
Organic						
Between lakes	4	1,673.20	418.3	21.10	20.90	11.28
Between samples	10	198.2	19.8	31.26		3.99
Within replicates	36	22.8	0.6			
Total	50	1,894.2				
Carbonate						
Between lakes	4	4,939.9	1,235.0	462.91	459.27	11.28
Between samples	10	26.7	2.7	4.79		3.99
Within replicates	36	20.1	0.6			
Total	50	4,986.6				

F's the variance ratio after correction for the unequal sample sizes

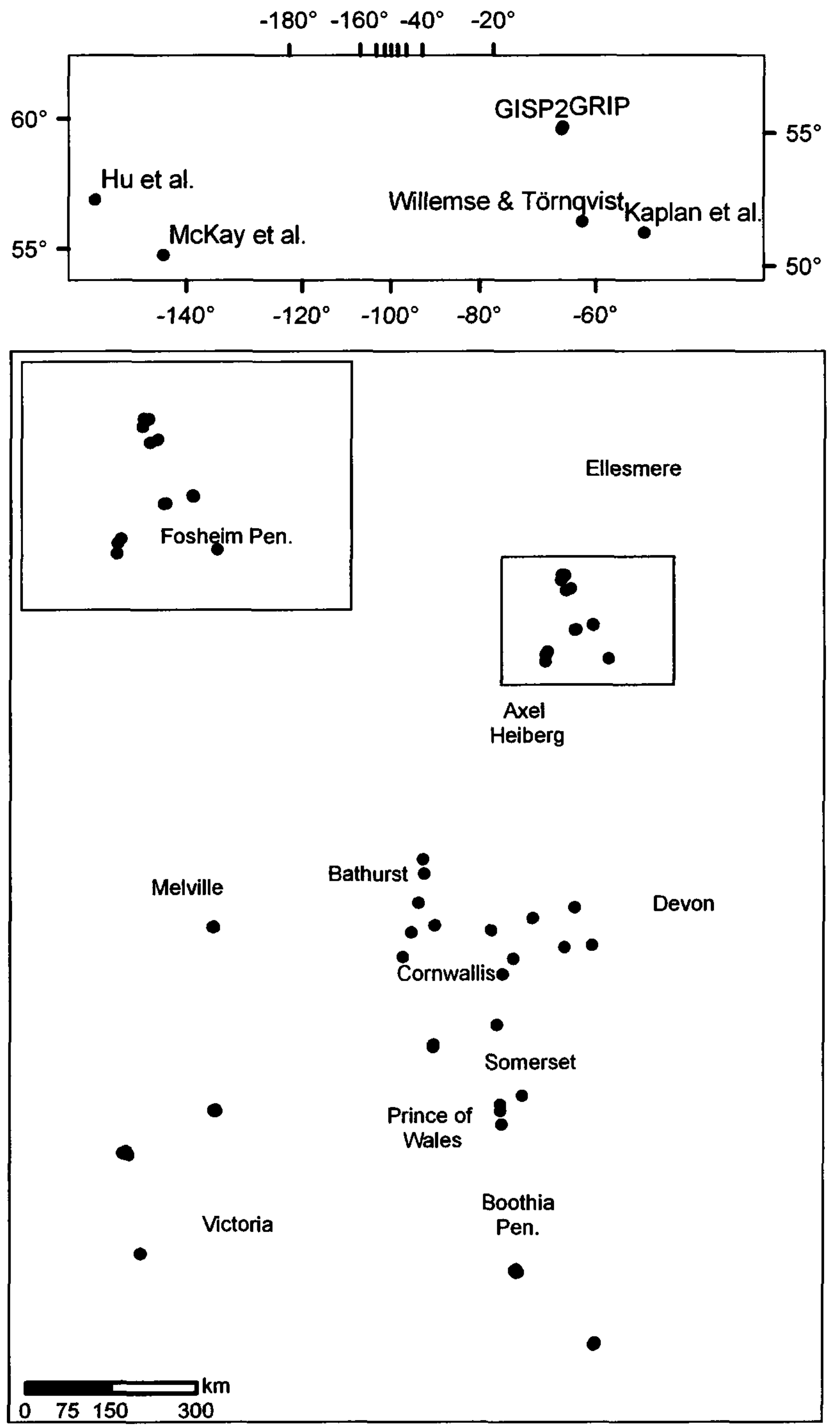

Figure 1 Location of the 63 lakes included in this study. The *top map* shows the location of the sites referred to in the text

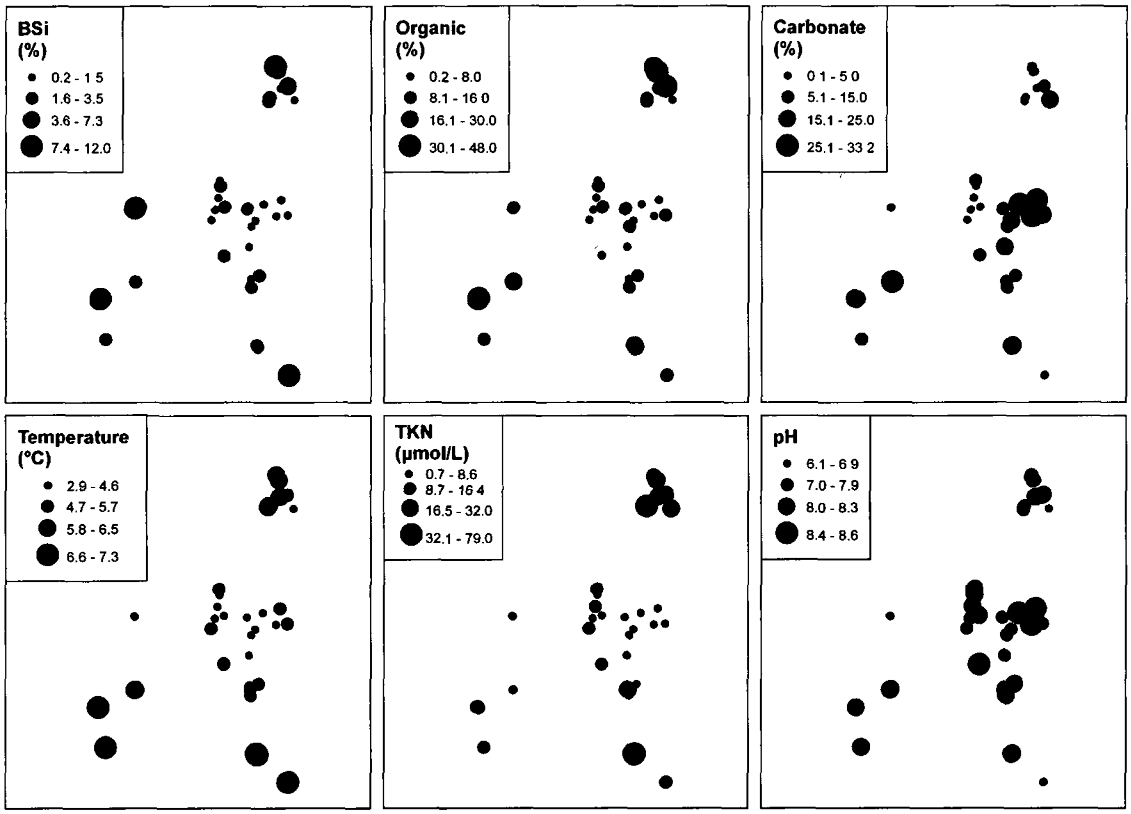

Figure 2 Mapped patterns of biogenic silica, organic and carbonate sediment content (weight %) and mean July air temperature (°C), lake water TKN (µmol L^{-1}) and pH for 63 Arctic lakes. Mean July air temperatures extracted from Atkinson and Gajewski (2002)

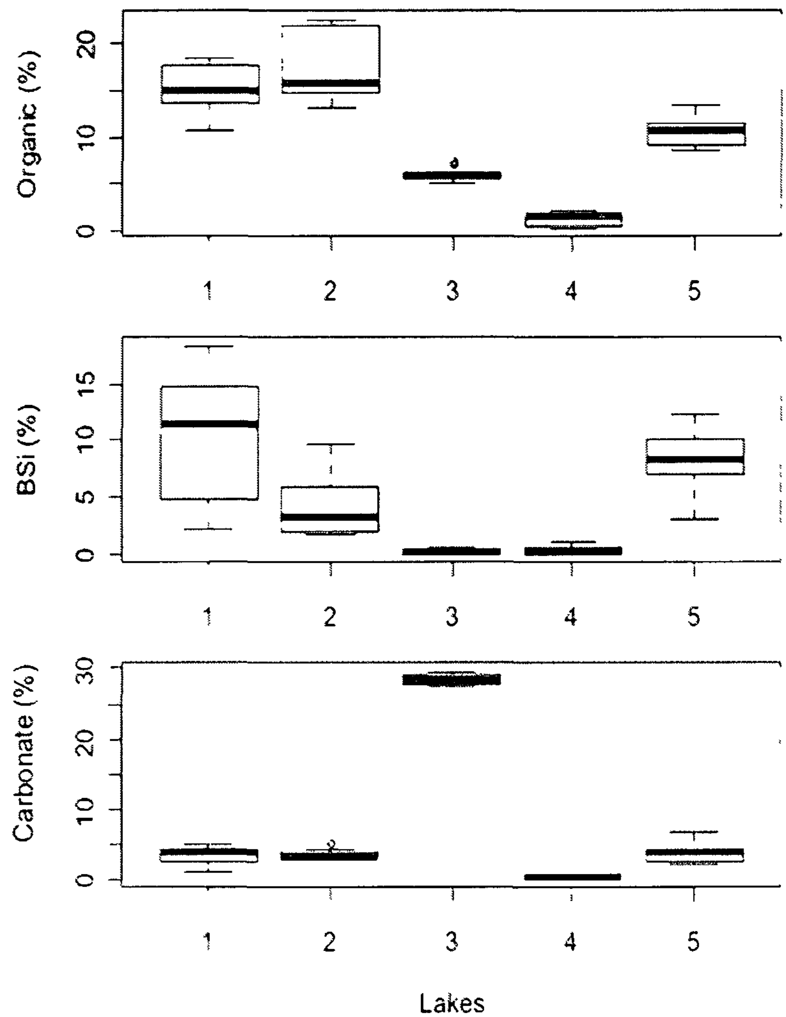

Figure 3 Box plot comparing sediment organic, biogenic silica and carbonate content (weight%) within and among a series of five lakes. Lake 1 is located on Melville Island, lake 2 on Ellesmere Island, lake 3 on Devon Island and lakes 4 and 5 on Southern Boothia Peninsula. For details regarding sampling size refer to Table 2

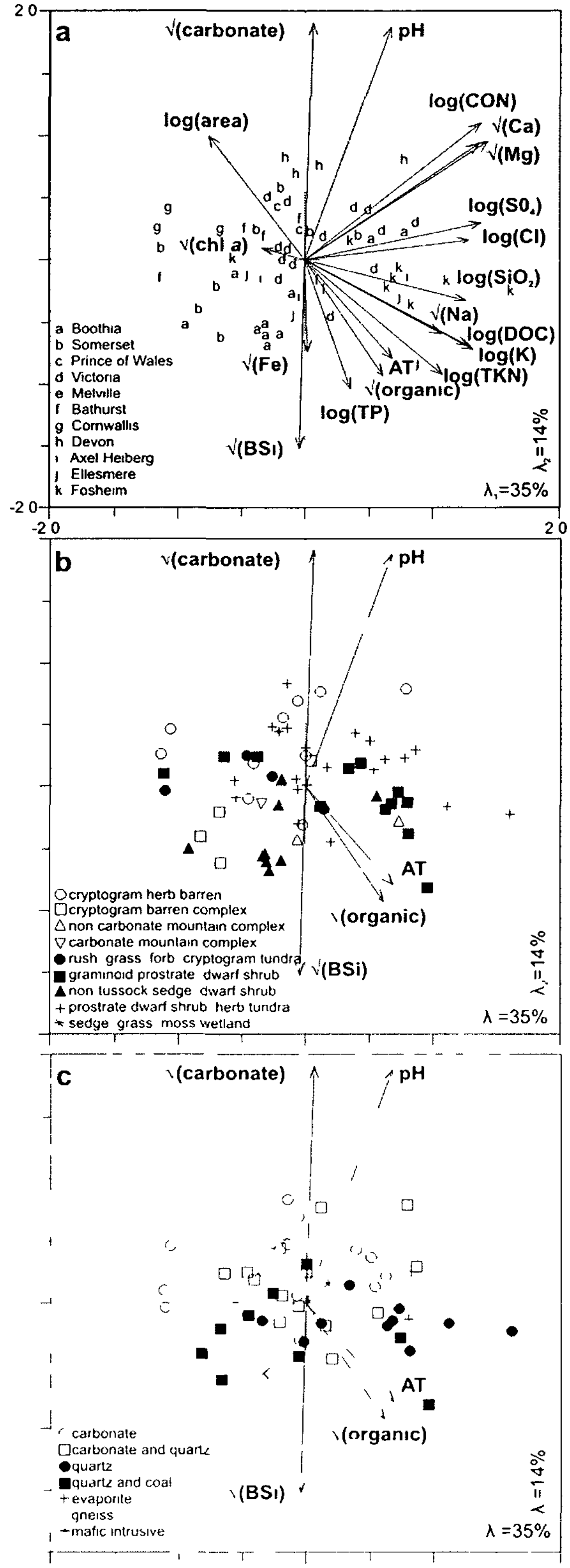

Figure 4 Biplot of the first two components of a principle component analysis showing the relationship among sediment biogenic silica, organic and carbonate content, mean July air temperature (AT) and the other major environmental, physical and chemical parameters of 63 Canadian Arctic lakes. The lakes are classified by **a** their location, **b** surrounding vegetation (CAVM Team, 2003) and **c** bedrock composition (Okulitch, 1991). Parameters used in the PCA were transformed and labeled correspondingly

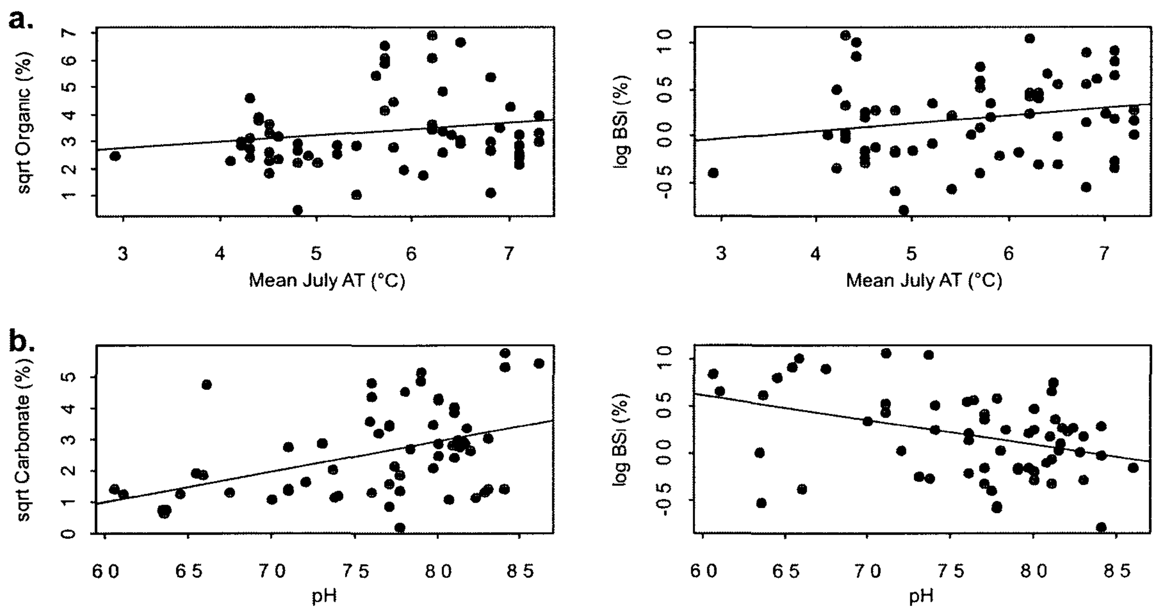

Figure 5 Scatter plot of the relationship between **a** sediment organic content (%) and mean July air temperature (AT) (°C), sediment biogenic silica content (%) and mean July air temperature and **b** sediment biogenic silica content (%) and water pH and sediment carbonate content (%) and water pH. The line in each plot is a regression line

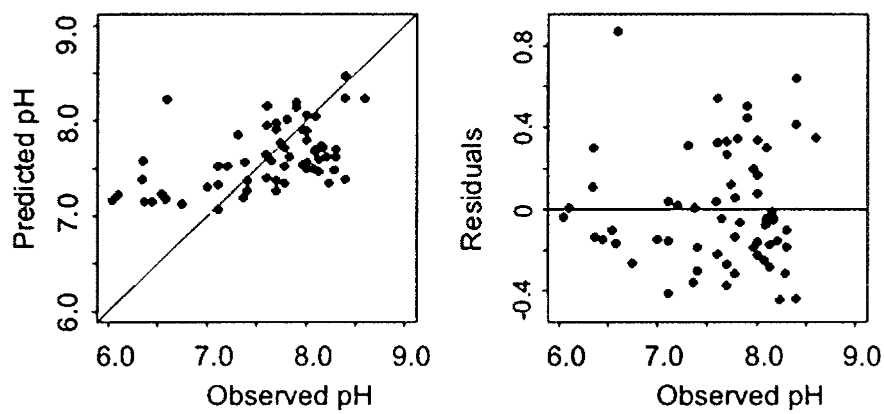

Figure 6 Results from an inference model showing predicted lake water pH and observed lake water pH, (with 1:1 line) and residuals and observed lake water pH

Chapter 3

Methodology of the study of chironomid-environment relations in the Arctic

Marie-Claude Fortin*, Konrad Gajewski

Keywords: Chironomid, Training set, Canadian Arctic, Weighted averaging, Environmental reconstruction, Inference model, Mean July air temperature

Abstract

The distribution and abundance of chironomids across the Canadian Arctic was analyzed in relation to major environmental gradients of the region. Mean July air temperature, lake morphological characteristics and organic matter in the lake systems are important controls on chironomid abundance and distribution in the Arctic. Chironomids from these 88 lakes were used to develop an inference model for reconstructing past mean July air temperatures in paleolimnological studies. Methodological decisions made when developing paleoenvironmental inference models were explored. Decisions regarding the exclusion of rare taxa have little influence on the resulting models. However, the data used to characterize the physical environment can have a significant effect on the inference model. In particular, the use of gridded air temperature data must be approached with caution, as mesoclimates not estimated by the gridding process in a data-poor region can influence interpretation of fossil assemblages.

Introduction

Environmental reconstructions of past conditions based on lake sediment cores are used to assess the impact of climatic change on aquatic ecosystems through time. Past environmental conditions can be inferred from the fossil assemblages of organisms preserved in the sediment matrix. Many groups of organisms, such as fossil pollen grains, diatom valves and chironomid head capsules preserved in lake sediment are often used in these studies.

To reconstruct past environmental conditions based on a fossil organism, the modern relationship between this organism and present-day environmental conditions needs to be quantified. To do this, a modern "training set" is developed. This involves collecting data from a geographical series of lakes, including samples of the sediment, from which the microfossils are extracted and identified, as well as some measures of the physical-chemical environment. The results are two matrices: one containing environmental data for each lake and the other containing information regarding the fossil assemblages in the sediment matrix. Through analysis of the modern calibration data sets it is then possible to generate statistical models which, when applied to the downcore fossil data, will allow for the reconstruction of a particular environmental variable at that lake through time.

Several chironomid-based training sets have been developed in North America and a number of these include Arctic sites. Barley et al. (2006) developed the largest chironomid training set containing Canadian Arctic sites, that extends from the southern British Columbia border to the Canadian Arctic Islands, and contains 136 lakes located in Western Canada, with 23 of these on Arctic islands. This data set includes some, but not all, of the 50 sites from a study by Gajewski et al. (2005) from the Canadian Arctic Islands. Wilson and Gajewski (2004) studied 39 lakes in a small region of the southwest Yukon. Walker et al. (1997) constructed a smaller training set for Eastern Canada that consisted of 40 sites, including six Arctic sites on Baffin Island and Devon Island. This set was subsequently expanded by Francis et al. (2006), who added 28 new sites from Baffin Island. A northern Québec training set contains 60 lakes (Larocque et al., 2006), and more recently Porinchu et al. (2009a) developed a 77-lake chironomid training set for the central Canadian Arctic. This latter study includes sites from treeline through central Victoria Island. Only the Wilson and Gajewski (2004) and Gajewski et al. (2005) data sets are publicly available. These training sets were developed primarily to reconstruct past summer air temperatures using downcore fossil records from the regions covered by their respective training sets. However, issues still remain regarding the quality of the environmental data obtained for these training set studies, including both water conditions (Bunbury and Gajewski, 2008) and air temperature data (Walker and Cwynar, 2006).

Presently, there are no chironomid-based training sets available that cover the entire Canadian Arctic with a reasonable density of sites. However, given the growing importance of understanding the impact of future climate change in the Arctic region, it is important to develop and make available the proper tools with which researchers can infer past climatic conditions in this region. The objective of this study is to present chironomid data from across the Canadian Arctic and develop a robust chironomid-based transfer function that can be used in Arctic cores to generate reconstructions of past July air temperatures.

Methods

Field sampling

Surface sediment, water samples and environmental data were collected from 91 lakes from across the Canadian Arctic Archipelago. Results from 50 of these lakes were presented in Gajewski et al. (2005), and 41 are presented here for the first time (Figure 1; Table 1). All field work was conducted between 1992 and 2008 during spring or early summer. Surface sediment was collected from the deepest area of each lake using either a Livingston piston corer or a Glew surface corer. Samples were extruded in the field at 0.5cm or 1 cm intervals. Water samples were also collected at each site and subsequently analysed for water chemistry. Sediment and water samples were kept refrigerated (~5°C) until analysed.

Chironomid data

Lake surface sediment samples were analysed for chironomids, and chironomid extraction and mounting followed standard protocols (Walker et al., 1991). Chironomid identifications from Gajewski et al. (2005) were subsequently revised by Barley et al. (2006) to update the taxonomical resolution of the identifications. No significant differences regarding the major taxa of the training set existed between the original and revised data, and it is this revised chironomid data that was used in our study. The chironomid identifications for the 41 new lakes primarily followed Brooks et al. (2007), Heiri et al. (2004) and Barley (2004). Other reference material used included Wiederholm (1983), Oliver and Roussel (1983), Walker (1988; 2000) and Larocque and Rolland (2006). *Zalutschia* spA and spB are according to Barley et al. (2006). Taxa were identified to the species level when possible but consolidated when necessary to ensure taxonomic harmonization between studies.

The objective was to obtain a minimum of 50 head capsules (HC) per lake surface sample (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001). Using lower minimum head capsule counts can potentially increase the prediction error of the resulting statistical models (Heiri and Lotter, 2001). However, obtaining sufficient numbers of head capsules is not always possible in Arctic samples, since biological production, including that of chironomids, in these colder regions can be very low (Gajewski et al., 2005; Bunbury and

Gajewski, 2008, Porinchu et al., 2009a). Removing lakes based solely on low HC counts generally means reducing the number of lakes included in the training set from the lower end of the production gradient (Fortin and Gajewski, 2010a [5]; 2010b [6]) potentially biasing any reconstructions. A more inclusive yet still relatively conservative minimum of 35 HC was used in this study (Quinlan and Smol, 2001). Of the 91 lakes originally in the training set, three lakes (HB02 and MR03/04) had less than 35 HC and were not included in the remainder of the analysis. A total of 88 lakes were therefore retained for data analysis, including 5 lakes containing 40-50 HC and one lake, KR08, with 37 HC.

Environmental data

The environmental data for the new Arctic lakes are presented in Table 1. All water samples were analysed following guidelines provided by Environment Canada's Analytical Methods Manual (Environment Canada, 1994).

In many paleoenvironmental studies, reconstructing air temperature is often of primary interest. Due to the inherent variability associated with in-situ water or air temperature measurements (Bunbury and Gajewski, 2008), mean July air temperatures are commonly extracted from gridded data sets (e.g., Gajewski et al., 2000a; 2002; Hamilton et al., 2001; Whitmore et al., 2005; Barley et al., 2006). Two different mean July air temperature gridded data sets are available for the Canadian Arctic: New et al. (2002) and Atkinson and Gajewski (2002). Because of the availability of this high-resolution and improved Atkinson and Gajewski (2002) data set in the Canadian Arctic, we compared analyses using the global-scale New et al. (2002) data (JTemp_New) to those using the regional Atkinson and Gajewski (2002) data (JTemp_Atk). Does the choice of input data make a significant impact on the resulting reconstructions?

The New et al. (2002) set is a global data set with a geographic resolution of 0.5 degrees over the Canadian Arctic and is interpolated from surface data collected at standard meteorological stations. Since all of these stations are located on the coast and therefore present a biased picture of the July temperatures in the region, Atkinson and Gajewski (2002) developed a new climate dataset for the Canadian Arctic. The Atkinson and Gajewski (2002) gridded set only contains data for the Canadian Arctic, but has a finer spatial resolution with a 1 km grid, and further corrects temperatures according to a site's distance from the coast and elevation. Radiosonde data for the time period in question is used to develop a three-dimensional model of the atmosphere at daily intervals for 17 years. In ArcGIS, the temperature of every gridcell was extracted based on the altitude. Then the cooling coastal effect was corrected for by using the prevailing wind and correction factor based on distance from coast.

Mean July air temperatures were extracted using the nearest neighbour for all lakes using both data sets (JTemp_New, JTemp_Atk) in ArcGIS (Table1). Sediment organic content (LOI %) was also evaluated for all lakes following standard weight loss-on-ignition technique (Dean, 1974) (Table 1).

Only environmental and limnological variables with fewer than <10% missing values (of the total number of lakes) and with less than 50% of their values below detection limit were included in statistical analyses. A total of 18 environmental variables were retained. Mean values replaced missing values, and the midpoint between zero and the detection limit were used to replace values below detection. Transformations were performed on the environmental data which did not present normal distributions. Lake surface area (SA), conductivity (Cond), sediment organic content (LOI), dissolved organic carbon (DOC), total Kjeldhal nitrogen (TKN), total phosphorus (unfiltered) (TP_{unf}), nitrate-nitrite (NN), Cl, SO_4^{2-}, K and Na were all log transformed; depth was ln(x+1) transformed, where x is the environmental variable; SiO_2, Ca and Mg were square root transformed and JTemp_New, JTemp_Atk and water pH remained untransformed.

Species rarity criteria

In numerical analyses, a number of different taxa inclusion criteria can be used to determine which chironomid taxa to retain; typically rare taxa found in only a few sites are excluded from numerical analysis. We wanted to evaluate the impact of using different taxa inclusion criteria and transformations (Koster et al., 2004) on the resulting ordinations. Different versions of the Arctic chironomid data were therefore created based on five different taxa inclusion criteria frequently used in the chironomid literature. Complete ordination analyses (described in the next sections) were conducted on each of the different versions of the training set. The taxa selection criteria were to include only taxa with 1) relative abundance average >1% for all lakes (e.g., Fortin and Gajewski, 2010a [5]); 2) relative abundance >2% in two or more lakes (e.g., Walker et al., 1997; Wilson and Gajewski 2004, Gajewski et al., 2005 and Larocque et al., 2006, Fortin and Gajewski, 2010b [6]); 3) presence in >5% of lakes (e.g., Barley et al., 2006; Bunbury and Gajewski, 2008). We further created versions by 4) automatically downweighting rare taxa (e.g., Porinchu et al., 2009a); and 5) keeping all original taxa data untransformed.

Ordination

The ordination analysis was conducted using CANOCO (ter Braak and Šmilauer, 2002). A detrended correspondence analysis (DCA) was used to determine if unimodal or linear statistical methods applied. Based on the result of this analysis, a canonical correspondence analysis (CCA) (unimodal statistics) was performed on the data.

Inference model

Chironomid-based mean July air temperature inference models were developed using C2 (Juggins, 2003). Based on a detrended canonical correspondence analysis (DCCA) constrained to only temperature (gradient length 1.3 S.D. units) (Birks, 1995), and based on the DCA performed on all the data (gradient length 2.8 S.D. units) (ter Braak and Šmilauer, 2002) both unimodal and linear inference models were developed. Species relative abundances were always square root transformed and in all cases models were cross-validated using bootstrapping (1,000 cycles). Unimodal weighted averaging (WA) and weighted averaging partial least squared (WAPLS) as well as linear partial least squared regression techniques (PLS) were performed and evaluated.

The robustness of each of the regression models was determined based on performance statistics including bootstrapped coefficients of determination (r^2_{boot}), root mean squared error of prediction (RMSEP), maximum bias (max_bias_{boot}), and by examining the scatter plots of reconstructed versus observed values as well as the scatter plots of their residuals.

The WA model provided information regarding species mean July air temperature optima and tolerance. It is suggested that taxa with $N_2>5$ in the training set have reliable inferred environmental optima and tolerances (Brooks and Birks, 2001). In our Arctic training set, all taxa except *Corynocera ambigua*-type ($N_2=2$) had N_2 values greater than five ($N_{2avg}= 26$; $N_{2max}=78$).

Results

Chironomid assemblages

A total of 35 taxa were identified in the Arctic training set (Figure 2). The most abundant taxa were those from the genus *Micropsectra* spp. and subtribe Tanytarsina, with *Micropsectra* spp. taxa more abundant in the central islands (Melville, Bathurst, Cornwallis and Devon Island) and Tanytarsina-other with highest relative abundances in samples from Ellesemere Island (Fosheim area) and in the more southern islands (Somerset, Prince of Wales, Victoria and Banks Island as well as Boothia Peninsula). The remainder of the chironomid assemblages were mostly comprised of taxa from the Orthocladiinae subfamily, as is often the case in colder regions. A number of taxa including *Parakiefferiella nigra*-type, *Chironomus* spp, *Zalutschia* spA and spB, *Procladius*, *Psectrocladius (Psectrocladius),* Pentaneurini-other, and *Stictochironomus* were present on Ellesemere Island, absent from the central islands (Melville, Bathurst, Cornwallis and Devon Island) and then present again in the lower latitude lakes. *Hydrobaenus/Oliveridia*, *Pseudodiamesa* and *Paracladius* had the opposite distribution, with highest relative abundance in central Melville, Bathurst, Cornwallis and Devon Island. *Abiskomyia* is regionally constrained to lakes of lower latitude (below lat 73° d.d.).

Data analysis

JTemp_New vs JTemp_Atk

Temperatures extracted from the New et al. (2002) data set (JTemp_New) were on average 1°C ± 0.8 °C cooler than those extracted from the Atkinson and Gajewski (2002) data set (Jtemp_Atk) (Figure 3). JTemp_New ranged from 2.0°C to 7.0°C (mean 4.5°C), and the JTemp_Atk from 2.9°C to 7.3°C (mean 5.6°C) (Table 1), results that are statistically different (one tailed paired t-test, $p=7.8E^{-24}$). A significant correlation did exist between JTemp_New and JTemp_Atk ($r^2=0.59$, $p<0.001$), although this is certainly inflated by the spatial auto-correlation in both these data sets (Fortin and Dale, 2005).

In addition to the overall cold bias of the New et al. (2002) data, the magnitude of the difference in temperature varied geographically (Figure 3). The largest difference (~2°C) between JTemp_New and JTemp_Atk is located in the Fosheim region (Figure 1) of Ellesmere Island and adjacent Axel Heiberg Island, near the meteorological station of Eureka (Figure 3). The JTemp_Atk for the Fosheim region lakes were much warmer than sites located to the south of the region, whereas those estimated from the New et al. (2002) grid were comparable to those of lakes from surrounding regions. In fact, many of the Fosheim lakes were generally estimated as the coldest lakes when using New et al. (2002) temperatures. In reality, the Fosheim region is characterised by anomalously high summer temperatures and overall high terrestrial and lacustrine production for its location in the Arctic (Garneau and Alt, 2000; Fortin and Gajewski, 2009 [2]) and the Atkinson and Gajewski (2002) gridded data, with its higher spatial resolution and its ability to account for relief, appears to better estimate the warmer mean July air temperatures of this Fosheim region.

The only limitation in using the Atkinson and Gajewski (2002) data set to generate air temperatures is that it is limited to the Arctic Islands. This renders comparison to other studies difficult, or inhibits the development of a larger, more comprehensive chironomid training sets. In the remainder of this study, only the JTemp_New will be retained, although the known bias of these data will be considered in the interpretation of the results.

Chironomid-environment relationship

As a result of an exploratory data analysis (EDA) (including a principal component analysis (PCA) performed on the chironomid data, not shown), none of the 88 lakes retained for analysis were identified as being outliers or as having unusual chironomid assemblages.

The implications of using different taxonomic inclusion criteria were assessed next. In general, the taxonomic richness of the different version of the training set was relatively low, ranging from 13 to 35 taxa depending on the inclusion criteria used. No significant differences existed between the results of the ordination analysis including different subsets of the chironomid data (Table 2). As all taxa inclusion criteria generated similar results, we decided to retain taxa with relative abundance ≥2% in more than two lakes for the ordination analysis as this criterion seems most frequently used.

Ordination analysis

A detrended correspondence analysis (DCA) with detrending by segments and species data square-root transformed was used to determine species gradient lengths for the first axis of the DCA (Hill and Gauch, 1980). Since the gradient length for our analysis was 2.8 SD units, we felt it appropriate to use a canonical correspondence analysis (CCA) (Birks 1995; Lepš and Šmilauer, 2003). According to current ideas of the niche, we would expect taxa to have a unimodal distribution in relation to an environmental gradient. As a check, a redundancy analysis, which assumes a linear relationship between taxa and an environmental gradient was also performed and the results of both the CCA and RDA analyses were comparable.

A series of preliminary canonical correspondence analyses (CCA) constrained to each environmental variable (excluding latitude, longitude and distance from coast) were then performed on the data to determine which variables significantly affected chironomid distribution. Explained variance (e.g., statistics such as r^2, loadings, eigenvalues, etc.) is typically used to determine the influence of these individual environmental variables on the chironomid community composition. The idea is that if the r^2 of an environmental variable is high, this variable is "more important" in controlling the abundance and distribution of that chironomid community (e.g., Smol, 2002). However, this approach is problematic, as the r^2 depends on the structure of the data (the inter-site variability or the spatial autocorrelation) of the data as well as the actual strength of the relationship (Gajewski, 1983; Bryson, 1985; Telford and Birks, 2005; Bini et al., 2009). This would be particularly important with variables such as July temperature, where the development of the gridded data set induces strong spatial auto-correlation in the data (Telford and Birks, 2009). As such, the purpose of this step is not to find the controlling or "best variable" but simply to find those variables that can be statistically calibrated; that is, for which a reasonable statistical model can be developed. The CCA analyses were used to determine the pool of environmental variables which affect the chironomid distribution instead of attempting to identify the one most important variable.

Separately, five environmental variables explained significant (where spatial autocorrelation is not accounted for) portions of the variance in chironomid species distribution ($p<0.05$, Monte Carlo permutations (499)): mean JTemp_New, lake surface area, depth, sediment organic content (LOI) and lake water DOC. These are reasonable results, as they indicate that temperature (which would have a physiological effect), morphological variables (which determine habitat), and carbon estimates (which are related to food supply) are all environmental variables that affect chironomid distribution. Another series of CCAs using only these five variables were then performed and leverage diagnostics were examined. Based on these leverage diagnostics, none of the five significant environmental variables were determined as collinear, since all variance inflation factors (VIF) were <10. Similarly, no single value from any lake in the training set was considered as having extreme influence (all had influence <8x). The five significant variables together explained 14.6% of the species variance on the first two CCA axes ($\lambda 1=0.17$ and $\lambda 2=0.09$ S.D. units). This explained species variance is comparable to that found in previous studies: 11.5% in Gajewski et al. (2005); 18.1% in Barley et al. (2006), 19.5% in Wilson and Gajewski (2004); 22.9% in Porinchu et al. (2009a).

The significance of the first two axes of the final CCA were confirmed ($p \leq 0.001$, Monte Carlo permutations (499)), and the relationship between these axes and the environmental variables were evaluated using canonical coefficients, t-values, and inter- and intra-set correlations. All forward selected variables were significantly correlated to the first axis and the JTemp_New, surface area and lake depth were also significantly correlated to the second CCA axis (Table 3). JTemp_New was negatively correlated to both axes (same magnitude on both axes), whereas lake surface area was positively correlated to the first axis and negatively correlated to the second (same magnitude). The biplot of the final CCA indicated that lower latitude lakes ordinated positively according to JTemp_New, as did *Corynocera oliveri*-type, *Corynocera ambigua*-type and *Zalutschia* spB taxa. *Eukiefferiella/Tvetenia* spp. and *Hydrobaenus/Oliveridia* spp. occurred in lakes in cooler regions. *Chironomus* spp. occurred in the shallower, smaller lakes. *Psectrocladius (Psectrocladius), Procladius, Pentaneurini-other*, and *Zalutschia* spA were most abundant in lakes with higher sediment organic and DOC content.

Transfer function development

A model was developed to reconstruct past mean July air temperatures from the chironomid fossil record, as a common interest in chironomid studies is to reconstruct past climates (e.g., Walker et al., 1997; Francis et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a; Fortin [3]). The model which best inferred JTemp_New was the weighted average ($WA_{tol/class}$) model with classical de-shrinking and tolerance downweighting (Birks, 1998; Juggins, 2003). The $WA_{tol/class}$ was the regression model that provided the best r^2_{boot} (0.42), and the overall lowest maximum $bias_{boot}$ (1.21°). The $RMSEP_{boot}$ (1.20°C) for the $WA_{tol/class}$ model was slightly higher than those of the other regression-based models (Table 4). There were no patterns in the residuals of the inferred JTemp_New versus extracted JTemp_New, therefore no bias is present in the model (Figure 5). The r^2_{boot} were comparable to those of other chironomid-based inference models from Europe (see Olander et al., 1999), but were significantly lower (0.25 to 0.46 lower) than those found in the North American studies that include Arctic sites (Walker et al., 1997; Larocque et al., 2006; Barley et al., 2006; Francis et al., 2006; Porinchu et al., 2009a).

Mean July air temperature optima and tolerances of the chironomid taxa were generated by the WA model. Temperature optima from this study were compared (Figure 6) to optima temperatures for the same taxa computed in Barley et al. (2006) and Francis et al. (2006). Mean July air temperatures for the Barley et al. (2006) study were extracted from New et al. (2002) whereas those for the Francis et al. (2006) study were extracted from another gridded dataset (Thompson et al., 1999) as well as estimated from climate atlases (see original publication for details).

Within the range of mean July air temperatures present in this study (2-7°C), *Potthastia*, *Hydrobaenus*/*Oliveri* spp. and *Eukiefferiella*/*Tvetenia* spp. had the coldest optimal temperatures (3.6, 3.9 and 4.0°C respectively) whereas *Corynocera ambigua*-type, *Zalutschia* spB and *Corynocera oliveri*-type the warmest JTemp_New (5.7, 5.8 and 5.9°C, respectively). Not only were the absolute values of the optima and tolerances different between the three studies (as expected), but the relative ranking varied as well (Figure 6).

Discussion

Important differences exist between the mean July air temperatures extracted from the New et al. (2002) and Atkinson and Gajewski (2002) data sets. The New et al. (2002) temperatures are a global data set and based on very limited surface coastal data from the Canadian Arctic. There will be a cold bias introduced in Arctic regions (Figure 3) when using data based on coastal stations (Atkinson and Gajewski, 2002). The Atkinson and Gajewski (2002) temperatures would be more accurate across the entire Arctic, especially in the interior of the islands, than those derived using New et al. (2002), due to the use of upper air data as well as those from the surface, and since it accounts for the well known influence of distance from coast, altitude and ice sheets on air temperature. When using the New et al. (2002) data, one must take into account that this data set appears to underestimate mean July air temperatures for the Arctic by ~1°C, and by up to ~2°C for the Fosheim region. The systematic underestimation is less of an issue, but the regional differences of greater magnitude may pose a significant problem, which is most apparent when inferring past mean July air temperatures by using the modern analogue technique (MAT), but would also be evident in model-based reconstructions; an example is shown in Chapter 7 of this thesis (Fortin, *subm* [7]).

The rarity criteria used to select taxa to include in statistical analysis did not significantly affect the results of the ordination analysis. JTemp_New explained, for all permutations, a comparable portion of variance in the assemblage as a function of the total inertia. It may be desirable to be more consistent in selecting a criterion, however, there is no statistical basis for any one of the criteria.

The only difference that may arise is when applying these equations in a core. If some rare taxon is found in a core, but not in the modern set, a non-analogue situation exists. Similarly, dominant taxa in a core found with values not in the modern set would be a more serious problem (Arigo et al., 1986). Nevertheless, inadequate representation in the modern data of taxa found in a core is not so much an issue regarding the taxa inclusion criteria but rather the inappropriateness of the training set used for the reconstruction. Therefore, although all taxa inclusion criteria generate the same results when analyzing the modern data, the results when applied downcore may not follow. Rare taxa could still be downweighted or removed in order to reduce the magnitude of the error at the reconstruction phase.

A chironomid-based inference model, using the $WA_{tol/class}$ (three components), was developed to reconstruct past mean July air temperatures. The significant relationship between summer air temperatures and chironomid assemblages was also observed in other Canadian chironomid-based studies (Walker et al., 1997; Wilson and Gajewski, 2004; Barley et al., 2006; Francis et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a). The shorter temperature gradient, as well as the strong influence of other variables such as lake surface area, may account for the slightly lower performance statistics of the inference model. Also, as Walker and Mathewes (1989) noted, given both the aquatic and terrestrial phases of chironomid development it is unlikely that one measure of either air or water temperatures could fully account for the influence of temperature on these organisms.

However, mean July air temperature was not the only important variable affecting chironomid species distribution. Lake morphological features such as surface area and lake depth explained a significant amount of variance in species data. Lake depth was also found to be important by Porinchu et al. (2009a), Larocque et al. (2006) and Barley et al. (2006). Barley et al. (2006) and Walker and Cwynar (2006) have suggested that the distribution of chironomids in colder regions is more affected by temperature than are assemblages at lower latitudes, and that, furthermore, the effect of temperature in the Arctic far outweighs that of any other variable. Indeed, studies from the eastern Arctic (Walker et al., 1997; Francis et al., 2006) only examined air temperature as a factor that controls chironomid abundance. In general, it is difficult to make such conclusions using the methodology discussed in these studies, as temperature would be more highly spatially autocorrelated than most limnological variables (Telford and Birks, 2009). From the results of this study, as well as Wilson and Gajewski (2004) and Porinchu et al. (2009a), lake morphological features are also important controls on the distribution of these taxa across the Arctic.

Sediment organic content was also determined as being an influential variable for chironomid species distribution and abundance. Although Walker et al. (1991) did not find a significant relationship between sediment organic content (LOI) and chironomid community composition in eastern Québec and Labrador lakes. Olander et al. (1999) and Wilson and Gajewski (2004) determined that it was an important factor in northern Fennoscandian and southwestern Yukon/Northern British Columbia, respectively. DOC was also found to be important factor in Québec lakes (Larocque et al., 2006). Sediment organic content is comprised of all plant and animal material produced in and around the lake, which is ultimately deposited on the lake floor. Since chironomids primarily feed off aquatic plant material and diatoms, it is not surprising that changes in food availability would be reflected in changes in chironomid community composition. Although it is tempting to assume that the changes in sediment organic content across the Arctic are primarily due to differences in air temperature, which would influence primary production, this is not necessarily the case, as bedrock composition and local factors complicate the relationship between temperature and lake production (Fortin and Gajewski, 2009 [2]).

Even after accounting for the variance explained by these five environmental variables, the unexplained variance in chironomid distribution across the Arctic still remains high. Factors not easily included in these training sets, such as predation, and chironomid intra-species competition to name a few, may be responsible for part of this unaccounted variance. Furthermore, the interaction between these different variables may also account for a portion of the variance in chironomid distribution.

The WA inference model generated optimal temperatures for the major chironomid taxa of the Canadian Arctic. These temperature optima were always lower than those generated for the same taxa by Barley et al. (2006) and Francis et al. (2006). This is expected, since these latter studies contain lakes with much warmer mean July air temperatures. The ordering of the taxa according to optimal temperatures is more similar between this study and the Barley et al. (2006) study than between this study and that of Francis et al. (2006). One reason for this is that both this study and Barley et al. (2006) used New et al. (2002) for July air temperatures, whereas Francis et al. (2006) used two different data sets to extract temperatures from Baffin, and then from the other sites in their study.

More importantly, differences still exist between these three studies regarding the relative ordering of these taxa. For example, in the present study, *Abiskomyia* is on the warmer end of the temperature gradient, while in both Francis et al. (2006) and Barley et al. (2006)—considering only taxa present in the Arctic training set—it is considered a cold-tolerant taxon. However, the absolute value of the temperature optima of *Abiskomyia* for all three training sets remains within ~2°C, which is one of the smallest differences in temperature optima between these studies. This suggests that all three training sets include most of *Abiskomyia*'s temperature range. For some taxa (for example, *Parakiefferiella nigra*-type or *Psectrocladius* (*Psectrocladius*) spp.) the relative position in relation to other taxa differs between studies, and the optimum varies greatly.

These differences in the relative order of the temperature optima are due to a number of factors including random errors associated with estimating the parameters of a normal curve using few data. An important factor is that each study covers not only different geographical regions but also different lengths of temperature gradient. If part of the environmental range is missing then the order of the species' optimal tolerance according to that environmental variable can be inaccurate (ter Braak and Looman, 1986). These large differences between the training sets' taxa optimal temperatures and order of taxa according to these temperatures will undoubtedly have significant repercussions on the resulting reconstructions.

The results presented here provide, for the first time, data from the large geographic expanse of the Canadian Arctic. It therefore offers the field of Arctic chironomid paleolimnological studies a sorely-needed series of data that are likely to be better analogues to conditions in the past than those currently provided by other training sets. However, if past environmental conditions in the Arctic were ever warmer than they are at all of the lakes in this study, the inferred past temperatures for these warm periods would inevitably be underestimated. This issue is most evident when using the MAT, as good modern analogues would not be available for these warmer periods, but it applies equally to other methods.

These results, especially the differences in the estimated optima, further demonstrate the necessity of developing larger chironomid training sets to ensure that the entire environmental gradients for all taxa in the training sets are captured. Furthermore, a standardization of the methods for obtaining temperature data for these training sets would greatly reduce the discrepancies between studies.

Conclusion

It is important to generate "robust" and consistent temperature data for paleoclimate calibration, and the best way to standardize this in regions with few data is to extract it using gridded datasets. However, there are important limitations associated with using global datasets such as New et al. (2002) that need to be considered when performing reconstructions. The July temperatures from Atkinson and Gajewski (2009) better estimates the regional mesoclimates of the Arctic (e.g., temperatures on Ellesmere) but its reduced spatial extent renders these data less useful.

Mean July air temperature, lake morphological characteristics and organic matter in the lake system are important controls on chironomid abundance and distribution in the Arctic. A transfer function based on 88 Canadian Arctic lakes that can be used for estimating July air temperatures in Canadian Arctic paleoenvironmental studies was developed. This is the only currently available training set that spans the Canadian Arctic with a reasonable density of sites and thus can be used to identify analogues for arctic assemblages in paleoenvironmental studies.

The current strategy in chironomid paleoenvironmental studies is to develop many local "training sets", and use these to estimate paleoclimates in lake sediment cores. However, smaller geographically constrained training sets do not sufficiently include the entire July temperature range of most taxa, and as such inadequately infer the optimal temperature of these taxa. This affects the robustness of the resulting reconstructions. As it is impossible to know *a priori,* for any taxon, their full environmental tolerance, and it is impossible to determine *a priori* the appropriate calibration set or equation to use for a set of fossil samples, the best approach is to develop larger, more regionally expansive training sets.

Table 1 Physical, environmental, and limnological variables for 91 Arctic lakes. The 41 lakes presented for the first time in this study are indicated by an *. Lakes MR03, MR04 and HB02 are not included in the analysis due to low chironomid head capsule counts but their environmental data are presented at the end of the table. Lakes are ordered according to decreasing latitude. LAT=latitude, LON=longitude, SA=lake surface area, Depth=water depth to sediment, LOI=sediment organic content as measured by loss-on-ignition at 550°C, JTemp_Atk=mean July air temperature extracted from Atkinson and Gajewski (2002), JTemp_New=mean July air temperature extracted from New et al. (2002), Cond=conductivity, DOC=dissolved organic carbon, TKN=total Kjedhal nitrogen, NN=nitrate-nitrite, TP_{unf}=total phosphorous unfiltered. Missing values indicated by NA, values below detection limit indicated by < detection value

Lake#	Lake name	LAT	LON	SA	Depth	LOI	JTemp Atk	JTemp New	Cond	pH	DOC	TKN	NN	TP_{unf}	SiO_2	SO_4^{2-}	Na	Cl	Ca	K	Mg
	unofficial	d d	d d	km^2	m	%	°C	°C	µS/cm		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
1	E509	80 83	84 45	0 023	4 0	21 2	5 5	3 3	32	7 1	2 4	0 14	0 046	0 006	1 240	1 8	0 4	0 9	7 7	0 200	0 6
2*	E508	80 81	84 16	0 160	2 6	20 2	5 8	3 9	50	7 6	2 7	0 15	0 001	0 008	1 400	4 3	49 9	1 4	52 0	3 700	11 0
3*	E510	80 75	84 68	0 137	9 0	29 4	5 6	3 3	39	7 2	2 4	0 20	0 001	0 008	1 100	2 1	0 5	1 2	8 0	0 200	0 7
4	E507	80 58	83 97	0 001	3 3	35 8	6 2	4 1	21	7 1	5 1	0 32	0 010	0 021	1 780	2 2	54 4	1 8	52 1	3 600	11 0
5*	E506	80 57	84 47	0 158	14 0	10 0	4 3	2 7	19	7 0	0 7	0 07	0 005	<0 005	0 880	2 1	0 6	1 3	3 0	<0 001	0 6
6	HW06	80 26	87 77	0 312	3 5	6 8	6 7	4 6	293	8 0	2 7	NA	0 010	<0 005	1 750	17 5	11 4	16 3	24 1	1 100	9 9
7	HW05	80 18	87 69	0 115	3 7	12 1	6 8	4 6	998	8 0	2 7	NA	0 010	0 006	0 350	2 1	101 0	202 0	38 9	4 170	17 5
8	HW01	80 02	83 39	0 057	3 7	17 6	6 7	5 0	366	8 2	8 6	0 19	<0 003	0 008	0 640	3 4	8 2	31 8	45 1	1 620	11 4
9	E505	79 98	82 97	0 004	2 5	11 7	6 0	3 5	56	7 1	2 2	0 17	0 005	0 009	0 530	2 8	0 5	0 6	5 2	0 300	1 1
10	Ridge	79 94	84 62	0 270	5 0	11 2	6 5	4 7	506	8 3	7 9	0 19	<0 003	0 008	0 690	7 4	38 2	57 9	37 1	3 700	18 1
11*	TwoBasin	79 93	84 67	0 003	5 5	9 6	6 5	4 8	569	8 3	4 5	0 22	0 002	0 004	1 200	4 3	48 1	32 0	39 0	4 683	NA
12	E504	79 93	82 94	0 006	8 1	15 2	5 7	3 5	27	6 9	3 9	0 26	<0 003	0 009	1 490	20 4	1 7	1 3	25 3	0 500	4 2
13*	Coal	79 93	84 53	0 005	1 4	8 5	6 5	4 7	1004	8 3	10 6	0 45	<0 003	0 010	0 800	25 5	100 4	113 5	45 2	9 740	7 1
14*	CV01	79 93	82 95	0 008	7 6	17 3	5 7	3 5	220	7 8	4 2	0 32	NA	0 011	0 860	43 0	3 1	1 6	30 0	1 430	6 6
15*	CV03	79 92	82 94	0 004	3 9	37 7	5 7	3 5	199	8 1	3 9	0 28	NA	0 011	0 620	49 0	1 7	1 1	27 0	1 430	9 8
16*	E503	79 92	82 93	0 005	3 5	35 3	5 7	3 5	26	7 1	4 9	0 41	0 019	0 013	2 250	73 3	2 6	2 2	57 0	0 900	11 4
17*	CV04	79 92	82 93	0 003	3 8	43 3	5 7	3 5	260	8 2	3 6	0 27	NA	0 010	0 730	75 0	2 3	1 2	35 0	1 760	NA
18*	CV02	79 92	82 93	0 008	3 2	34 8	5 7	3 5	190	7 7	1 4	0 15	NA	<0 005	0 540	45 0	1 3	0 6	24 0	0 520	6 8
19	HW03	79 73	85 81	0 150	13 0	5 2	3 9	2 0	524	7 8	1 1	NA	<0 003	<0 005	1 690	89 4	24 6	48 3	37 7	3 860	15 2
20	HW02	79 73	83 47	0 073	4 5	14 8	5 4	3 7	126	7 7	1 1	NA	<0 003	0 006	0 170	24 4	4 6	1 9	13 5	1 460	2 5
21	HW08	79 72	83 50	0 042	8 5	11 0	5 8	3 7	98	7 5	3 3	NA	<0 003	<0 005	0 150	5 0	4 2	1 3	12 1	0 520	2 1
22	HW07	79 72	83 52	0 061	6 0	21 2	5 8	4 1	79	7 3	3 6	NA	0 010	0 004	0 410	4 9	1 7	1 4	9 9	0 590	1 5
23	E516	79 69	87 51	0 633	3 0	6 6	5 8	4 4	162	7 7	13 5	1 10	0 010	0 006	1 120	111 0	2 1	3 6	58 7	0 700	3 2
24	E515	79 65	87 75	0 211	12 0	10 0	6 2	3 5	41	7 4	2 6	0 21	0 010	0 005	0 710	5 4	2 3	3 6	7 8	0 600	2 2
25*	E511	79 55	87 91	0 195	11 0	9 1	4 2	2 7	31	7 4	0 3	0 08	0 001	0 007	1 710	8 1	0 5	0 5	5 0	0 200	0 9
26*	E501	79 33	82 54	0 367	34 0	6 2	2 9	2 3	12	6 6	1 0	0 26	0 019	0 013	0 100	0 5	0 2	0 6	4 0	0 200	0 7
27	CI17	76 60	98 87	0 125	3 5	6 1	4 9	3 6	80	8 0	1 3	0 15	0 010	<0 005	0 370	3 7	1 8	1 9	17 5	0 510	2 5
28	CI18	76 51	98 88	0 094	5 5	17 7	5 0	3 6	50	7 8	1 2	0 16	<0 003	0 006	0 047	3 1	1 1	1 5	10 8	0 240	1 6
29	CI16	76 50	98 16	0 008	1 0	11 5	5 0	3 5	70	8 0	0 9	0 10	NA	0 007	0 192	0 8	1 2	1 7	16 3	0 152	2 1
30	CI15	76 50	98 16	0 059	4 0	14 0	5 0	3 5	30	8 2	0 7	0 12	<0 003	<0 005	0 009	0 5	1 0	1 5	9 0	0 126	0 7
31*	CI20	76 37	98 81	1 613	9 0	10 3	4 6	3 1	50	8 2	<0 5	0 07	0 010	<0 005	0 120	1 3	0 7	1 0	13 4	0 102	1 2
32	CI22	75 90	99 21	0 084	8 0	18 4	4 6	3 2	90	8 1	1 0	0 19	<0 003	0 022	2 100	7 5	0 5	0 4	23 0	0 690	2 9
33*	DV09	75 58	89 31	0 078	9 3	6 1	4 9	5 0	100	8 4	2 1	0 06	0 001	<0 005	0 300	5 9	1 9	2 9	27 0	0 200	5 2

Lake#	Lake name	LAT	LON	SA	Depth	LOI	JTemp Atk	JTemp New	Cond	pH	DOC	TKN	NN	TP_{unf}	SiO_2	SO_4	Na	Cl	Ca	K	Mg
		d d	d d	km^2	m	%	°C	°C	µS/cm		$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$
34	CI23	75 53	98 21	0 313	9 5	17 0	4 5	3 5	70	8 0	0 5	0 09	0 020	<0 005	0 138	0 4	0 7	0 8	18 9	0 111	0 5
35	DV07	75 53	91 97	0 219	5 0	13 7	4 4	4 3	148	8 4	1 2	0 08	0 010	<0 005	0 480	0 9	0 9	2 3	24 7	0 400	4 3
36	DV05	75 52	92 05	0 188	11 0	3 6	4 5	4 6	153	8 6	0 8	0 03	0 011	<0 005	0 280	1 3	0 9	2 3	24 2	0 200	4 3
37	CI25	75 52	99 53	0 225	3 0	11 8	4 8	3 6	140	7 8	2 0	0 16	<0 003	0 005	0 350	22 7	2 3	4 3	32 0	0 400	4 0
38	DV06	75 51	91 99	0 188	4 0	18 0	4 4	4 3	158	8 4	0 8	0 05	0 010	<0 005	0 470	0 6	0 9	2 1	25 8	0 200	4 4
39	CI27	75 46	99 91	0 196	4 0	8 8	4 9	3 7	6	8 4	<0 5	0 04	<0 003	<0 005	<0 003	0 2	0 4	0 5	0 6	0 041	0 0
40*	CI26	75 43	99 65	0 110	6 0	6 7	4 5	3 5	10	7 4	<0 5	0 06	<0 003	<0 005	<0 003	<0 1	0 0	<0 1	0 2	0 018	0 0
41	CI34	75 40	94 67	0 196	4 5	9 2	4 5	3 8	29	7 8	<0 5	0 08	0 010	<0 005	<0 003	0 7	0 3	0 7	4 2	0 060	0 8
42	DV08	75 37	89 49	0 138	3 0	3 0	4 7	4 5	175	8 4	0 8	0 03	0 010	<0 005	1 280	8 7	1 0	2 1	27 3	0 200	6 4
43	CI33	75 22	93 65	0 049	6 0	11 4	3 9	4 1	30	7 9	<0 5	0 04	0 010	<0 005	<0 003	0 9	0 6	0 8	7 3	0 060	1 0
44*	BC03	75 19	112 01	0 409	2 0	5 4	4 1	3 1	12	6 3	1 0	0 05	<0 003	0 005	0 152	0 9	0 6	1 1	0 4	0 158	0 4
45*	BC02	75 19	111 92	0 222	3 0	14 2	4 4	3 3	7	6 1	0 6	0 07	0 040	0 008	0 590	0 6	0 4	0 6	0 2	0 160	0 3
46*	BC01	75 19	111 92	0 237	11 3	15 2	4 4	3 3	5	6 6	0 5	0 07	<0 003	0 007	0 038	0 5	0 4	0 4	0 2	0 089	0 2
47	DV02	74 93	88 68	0 038	7 5	5 4	4 8	4 8	445	7 9	1 1	0 07	0 010	<0 005	1 280	395 0	2 3	4 2	140 0	0 400	17 2
48	CI32	74 91	93 52	0 165	8 0	8 2	4 3	3 9	10	7 8	<0 5	0 01	<0 003	<0 005	<0 003	0 1	0 2	0 3	2 1	0 015	0 1
49	DV04	74 83	88 23	0 063	5 5	2 8	4 8	4 7	99	8 1	0 8	0 08	0 019	<0 005	0 630	5 6	0 5	1 0	27 3	0 200	4 3
50	CI31	74 68	94 27	0 906	17 0	6 2	4 3	3 9	<5	7 7	<0 5	0 08	<0 003	<0 005	<0 003	<0 2	0 1	0 0	0 5	0 041	0 2
51	CI01	73 88	94 87	0 138	2 1	2 9	4 5	4 0	150	7 6	0 7	0 10	<0 003	<0 005	0 115	2 2	0 7	1 3	22 0	0 220	3 9
52	Allen	73 62	98 47	8 160	4 0	3 7	4 8	4 1	68	7 7	0 7	0 10	0 010	<0 005	0 480	2 3	0 8	1 7	11 6	0 200	4 4
53	DUO	73 58	98 45	0 001	0 3	20 8	4 9	4 1	23	8 6	7 4	0 77	NA	0 009	0 200	15 9	1 7	3 3	33 0	0 600	15 8
54	Wolf	73 58	98 48	0 407	6 0	3 8	4 9	4 1	65	8 4	1 3	0 15	0 010	0 005	0 490	4 1	0 8	1 6	14 6	0 300	5 3
55	CI14	72 70	93 87	0 213	5 0	7 3	4 0	5 0	<5	8 1	0 5	0 05	<0 003	<0 005	<0 003	<0 1	0 1	<0 02	0 1	0 008	0 1
56	CI07	72 59	95 06	0 319	5 5	29 3	5 4	4 8	80	7 8	1 8	0 15	<0 003	0 012	0 470	1 6	1 6	4 5	16 0	0 290	5 9
57	CI08	72 49	95 09	0 125	4 0	6 4	5 2	5 0	170	8 1	3 2	0 37	<0 003	0 024	0 058	25 1	2 2	3 9	28 0	0 660	13 2
58*	WB06	72 31	109 87	0 440	9 6	3 9	5 9	5 1	97	8 0	<0 5	0 10	<0 003	0 013	0 400	1 9	0 5	0 7	17 0	<0 001	5 5
59	WB05	72 29	109 83	1 535	14 3	3 3	6 1	5 1	99	7 9	1 0	0 08	<0 003	0 016	0 320	1 3	0 5	0 7	14 0	0 400	7 1
60	WB02	72 29	109 97	0 023	7 5	5 6	6 3	5 1	88	8 0	<0 5	0 06	0 018	0 065	0 470	3 1	0 6	1 0	26 0	0 200	5 0
61*	WB01	72 29	109 99	1 873	20 0	11 4	6 3	5 1	139	8 0	2 0	0 07	<0 003	0 071	0 470	3 3	0 5	1 8	23 0	1 400	5 1
62*	WB04	72 28	109 94	0 087	4 0	24 0	6 3	5 1	75	8 0	<0 5	0 08	0 010	0 012	0 530	3 8	0 5	0 5	23 0	0 300	5 8
63	CI09	72 27	95 09	0 213	4 0	5 6	5 4	5 0	30	8 2	0 5	0 09	<0 003	<0 005	0 038	1 6	0 6	0 9	6 3	0 149	2 1
64	CI12	72 03	94 62	0 095	9 5	6 5	5 7	4 8	60	7 9	0 8	0 10	0 010	<0 005	0 162	1 8	0 7	1 3	8 4	0 181	3 2
65	CI11	72 02	94 75	0 049	6 5	11 0	5 8	4 8	60	7 9	1 2	0 10	<0 003	<0 005	0 187	0 9	1 0	1 7	10 0	0 189	3 6
66*	MR02	71 72	122 04	0 045	4 2	32 1	5 8	4 8	74	7 8	2 2	0 14	0 020	<0 005	0 040	3 1	1 2	2 1	7 3	0 170	3 8
67*	MR01	71 72	122 04	0 991	21 0	11 2	5 8	4 8	173	8 2	1 5	0 08	<0 01	<0 005	0 260	8 0	2 0	3 7	18 0	0 320	9 0
68	KR07	71 36	113 81	0 360	5 6	46 7	6 3	4 7	155	7 6	2 2	0 23	<0 003	0 01	1 550	22 0	1 5	2 0	25 0	0 560	11 3
69	KR02	71 34	113 78	0 008	6 1	48 5	6 2	4 7	79	7 4	2 2	0 14	0 040	0 008	0 950	4 3	0 6	0 7	12 6	0 179	4 8
70	KR01	71 34	113 82	4 343	5 0	6 4	6 4	4 7	34	7 7	2 2	0 12	0 040	0 007	0 690	3 4	0 7	0 9	12 3	0 250	5 1
71	KR06	71 32	113 97	0 283	4 5	10 7	6 8	5 2	19	7 6	2 2	0 15	0 020	0 009	0 197	2 2	0 3	0 8	5 7	0 153	2 8

Lake#	Lake name	LAT	LON	SA	Depth	LOI	JTemp Atk	JTemp New	Cond	pH	DOC	TKN	NN	TP_{unf}	SiO_2	SO_4	Na	Cl	Ca	K	Mg
		d d	d d	km_2	m	%	°C	°C	µS/cm		$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$
72*	KR04	71 31	113 94	1 038	7 1	28 8	6 8	5 2	10	7 6	NA	0 10	0 010	0 013	0 210	1 6	0 3	0 6	5 7	0 188	3 0
73*	KR08	71 31	113 67	0 125	3 3	10 6	6 4	5 2	420	8 1	NA	0 19	0 020	0 007	1 610	128 0	1 5	1 7	78 0	1 760	18 8
74	JR02	69 92	94 97	2 100	3 0	17 1	7 0	6 3	198	8 0	3 1	0 72	0 017	0 03	0 604	0 9	1 6	3 0	33 4	0 615	16 4
75	JR01	69 90	95 07	0 210	5 4	35 0	7 1	6 3	220	8 1	4 7	0 81	0 024	0 04	1 210	2 4	2 1	5 1	42 4	0 557	21 7
76*	JR06	69 87	94 92	0 135	4 0	26 5	7 1	6 3	39	7 1	1 7	0 19	0 008	0 020	0 077	0 5	0 4	0 7	3 5	<0 001	1 2
77*	JR05	69 87	95 00	0 090	4 5	4 8	7 1	6 3	10	7 3	0 8	0 13	0 008	0 020	0 055	0 3	0 2	0 4	1 7	<0 001	0 8
78*	MB03	69 80	112 07	1 207	25 9	11 2	7 3	6 0	280	8 2	1 1	0 11	<0 003	<0 005	0 850	4 7	1 3	2 4	28 0	0 460	17 0
79*	MB02	69 80	112 08	0 080	31 5	9 0	7 3	6 0	280	8 2	1 8	0 15	<0 003	<0 005	0 600	9 7	1 3	3 5	29 0	0 470	17 0
80*	MB01	69 80	112 07	0 078	15 8	15 6	7 3	6 0	270	8 1	2 1	0 19	<0 003	0 005	1 100	15 1	1 3	4 1	27 0	0 460	16 3
81*	SL06	68 60	91 95	0 034	9 0	12 5	6 9	7 0	15	6 4	2 0	0 14	<0 003	0 011	0 142	0 7	1 1	1 6	0 8	0 360	0 5
82*	SL05	68 59	91 88	0 021	12 4	10 6	7 1	7 0	14	6 5	1 5	0 11	<0 003	0 008	0 036	0 7	1 1	1 6	0 8	0 320	0 4
83*	SL04	68 58	91 91	0 075	3 0	7 0	6 8	7 0	20	6 7	2 4	0 19	<0 003	0 013	0 136	1 5	1 3	1 3	1 3	0 620	0 7
84*	SL03	68 58	91 92	0 012	0 6	1 3	6 8	7 0	11	6 4	3 0	0 22	<0 003	0 016	0 220	0 4	0 6	0 7	0 5	0 520	0 4
85*	SL01	68 58	91 94	0 364	8 7	6 7	7 1	7 0	4	6 1	0 3	0 09	<0 003	0 009	<0 003	0 2	0 4	0 3	0 3	0 067	0 1
86*	SL02	68 57	91 96	0 111	8 7	8 2	7 1	7 0	16	6 5	2 1	0 15	0 030	0 011	0 014	0 8	1 2	1 8	0 8	0 470	0 5
87*	SP04	68 55	83 29	0 025	7 8	46 1	7 3	6 2	52	7 6	2 5	0 15	0 030	<0 005	0 120	0 7	0 8	0 9	6 9	0 410	1 5
88*	SP02	68 55	83 29	0 030	8 8	8 3	7 3	6 2	54	7 7	1 6	0 07	0 030	<0 005	0 070	0 6	0 6	0 5	7 6	0 250	1 6
89*	MR03	71 71	122 05	0 260	34 0	7 8	5 8	4 8	22	7 3	1 5	<0 02	<0 01	<0 005	<0 04	1 2	0 5	0 5	2 1	0 050	1 1
90*	MR04	71 71	122 06	0 071	11 3	9 0	5 8	4 8	68	7 7	2 1	0 10	0 050	<0 005	<0 04	4 4	1 7	3 0	5 8	0 140	3 4
91*	HB02	68 82	81 30	0 020	1 0	NA	2 0	5 8	152	8 1	4 1	0 42	<0 05	<0 005	0 680	2 9	4 8	7 2	24 6	0 920	2 7

Table 2 Summary statistics of a detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA) using different taxa rarity inclusion criteria. Included are the significant environmental variables and the added variance they each explain as identified through forward selection in CCA. JTemp_New extracted from New et al. (2002), SA=surface area, LOI=sediment organic content as measured by loss-on-ignition at 550°C, SD=standard deviation units, λ=eigenvalue

	All taxa untransformed n=35		**All taxa downweighting** n=35		**Relative abundance ≥2% in ≥ 2 lakes** n=24		**Present in ≥ 5% lakes** n=27		**Relative abundance ≥ 1%** n=13	
DCA										
Gradient length (SD) axis 1		3 124		3 124		2 781		2 801		2 703
Gradient length (SD) axis 2		2 214		2 214		2 162		2 186		2 087
CCA forward selection	Variable	Added variance	Variable	Added variance	Variable	Added variance	Variable	Added variance	Variable	Added variance
	JTemp_New	0 118	JTemp_New	0 103	JTemp_New	0 110	JTemp_New	0 113	JTemp	0 086
	SA	0 111	SA	0 100	SA	0 105	SA	0 105	SA	0 079
	Depth	0 050	LOI	0 042	Depth	0 046	Depth	0 049	DOC	0 031
	LOI	0 050	Depth	0 040	LOI	0 045	LOI	0 047	LOI	0 026
	DOC	0 043	DOC	0 034	DOC	0 012	DOC	0 037	TP_{unf}	0 025
			TP_{unf}	0 027			TP_{unf}	0 029	Depth	0 021
CCA all significant variables										
Total variance explained		0 372		0 346		0 318		0 380		0 268
Total inertia		2 351		1 576		1 772		1 764		1 118
λ1		0 175		0 167		0 170		0 176		0 133
λ2		0 096		0 090		0 089		0 101		0 074
Cumulative % variance of taxon data axis 1		7 444		10 596		9 594		9 977		11 896
Cumulative % variance of taxon data axis 2		11 527		16 307		14 616		15 703		18 515

all λ p<0 05

Table 3 Canonical coefficients with t-values and inter- and intra-set correlations for the first two axes for the CCA using taxa with abundance >2% in more than 2 lakes. JTemp_New extracted from New et al. (2002), LOI=sediment organic content as measured by loss-on-ignition at 550°C, DOC=dissolved organic carbon

	Canonical coefficient		*t*-values				Interset correlation		Intraset correlation	
	Axis 1	Axis 2	Axis 1		Axis 2		Axis 1	Axis 2	Axis 1	Axis 2
JTemp_New	-0.70	-0.67	-7.29	*	-5.46	*	-0.49	-0.48	-0.62	-0.69
Surface area	0.38	-0.55	3.45	*	-3.89	*	0.47	-0.46	0.59	-0.66
Depth	0.21	-0.40	2.09	*	-3.02	*	0.29	-0.43	0.36	-0.62
LOI	-0.32	-0.14	-3.07	*	-1.08		-0.37	0.09	-0.46	0.13
DOC	-0.32	0.02	-2.97	*	0.17		-0.52	0.13	-0.66	0.19

* $p<0.05$

Table 4 Performance statistics of the inference models and the modern analogue technique for reconstructing mean July air temperatures (JTemp_New extracted from New et al. (2002)). Only taxa with relative abundances ≥2% in more than two lakes were included in the analysis and where r^2=coefficient of determination, RMSE=root mean square error and RMSEP=root mean square error of prediction, WA=weighted average, WA_{tol}=weighted average with species tolerance downweighted, WAPLS=weighted average partial least squared, PLS=partial least squared. A 1,000 cycle bootstrapping was performed

Inference model		Apparent			Bootstrapped		
		r^2	RMSEP °C	Max bias °C	r^2	RMSEP °C	Max bias °C
WA	Inverse	0.48	0.83	1.80	0.38	0.94	1.98
	Classical	0.48	1.20	1.19	0.39	1.24	1.61
WA_{tol}	Inverse	0.51	0.80	1.64	0.41	0.93	1.75
	Classical	0.51	1.12	0.96	0.42	1.20	1.21
WAPLS	1 component	0.48	0.83	1.77	0.38	0.95	1.98
	2 components	0.57	0.76	1.67	0.39	0.98	1.98
	3 components	0.60	0.73	1.41	0.39	1.02	1.78
	4 components	0.61	0.72	1.36	0.37	1.08	1.77
	5 components	0.61	0.72	1.38	0.35	1.14	1.79
PLS	1 component	0.48	0.83	1.99	0.37	0.95	2.20
	2 components	0.56	0.77	1.81	0.41	0.93	2.06
	3 components	0.59	0.74	1.50	0.40	0.96	1.91
	4 components	0.61	0.72	1.57	0.39	0.99	1.83
	5 components	0.62	0.71	1.53	0.38	1.02	1.83

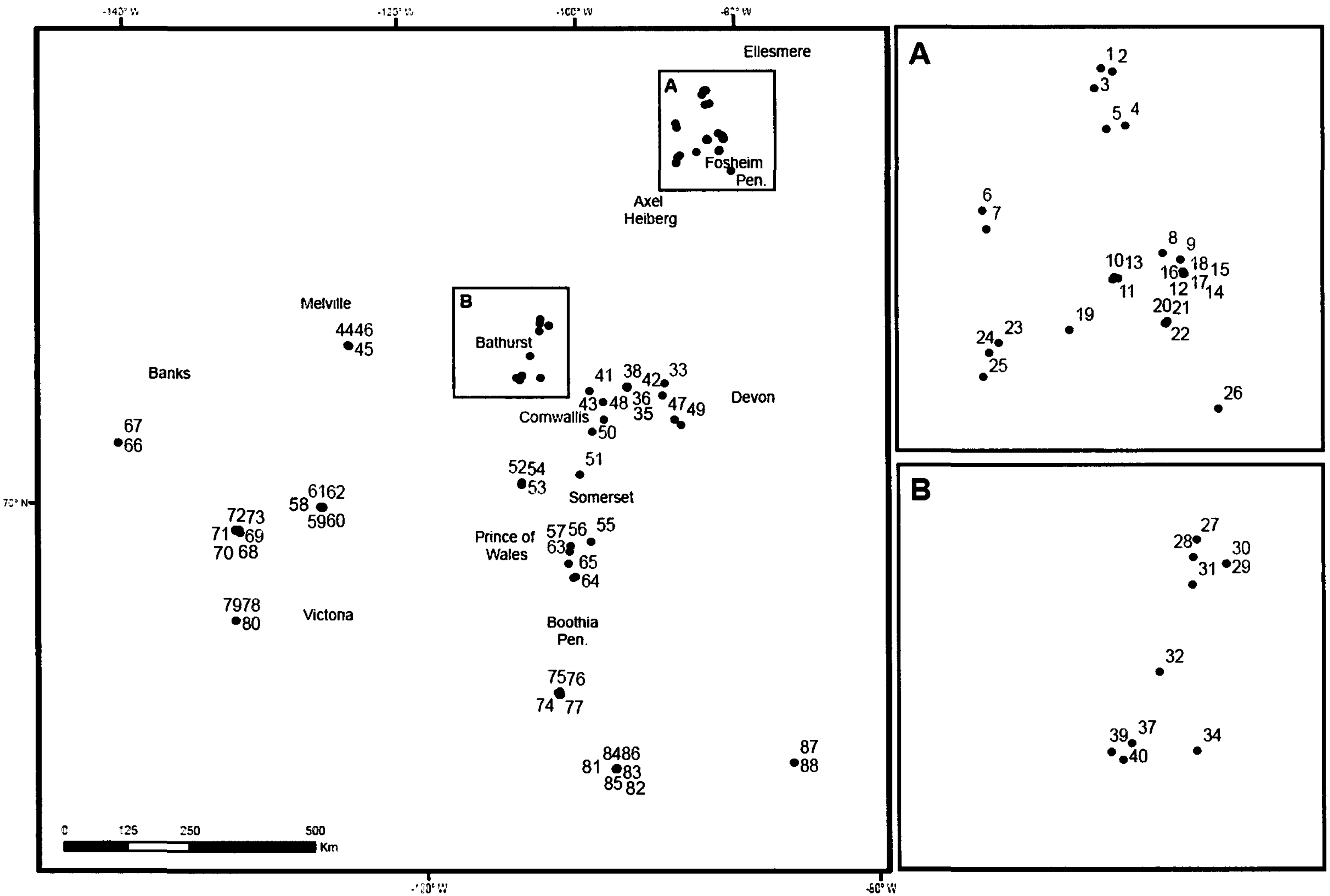

Figure 1 Location of the 88 lakes retained and analyzed in this study. Lake numbers are indicated on the map, see Table 1 for their names

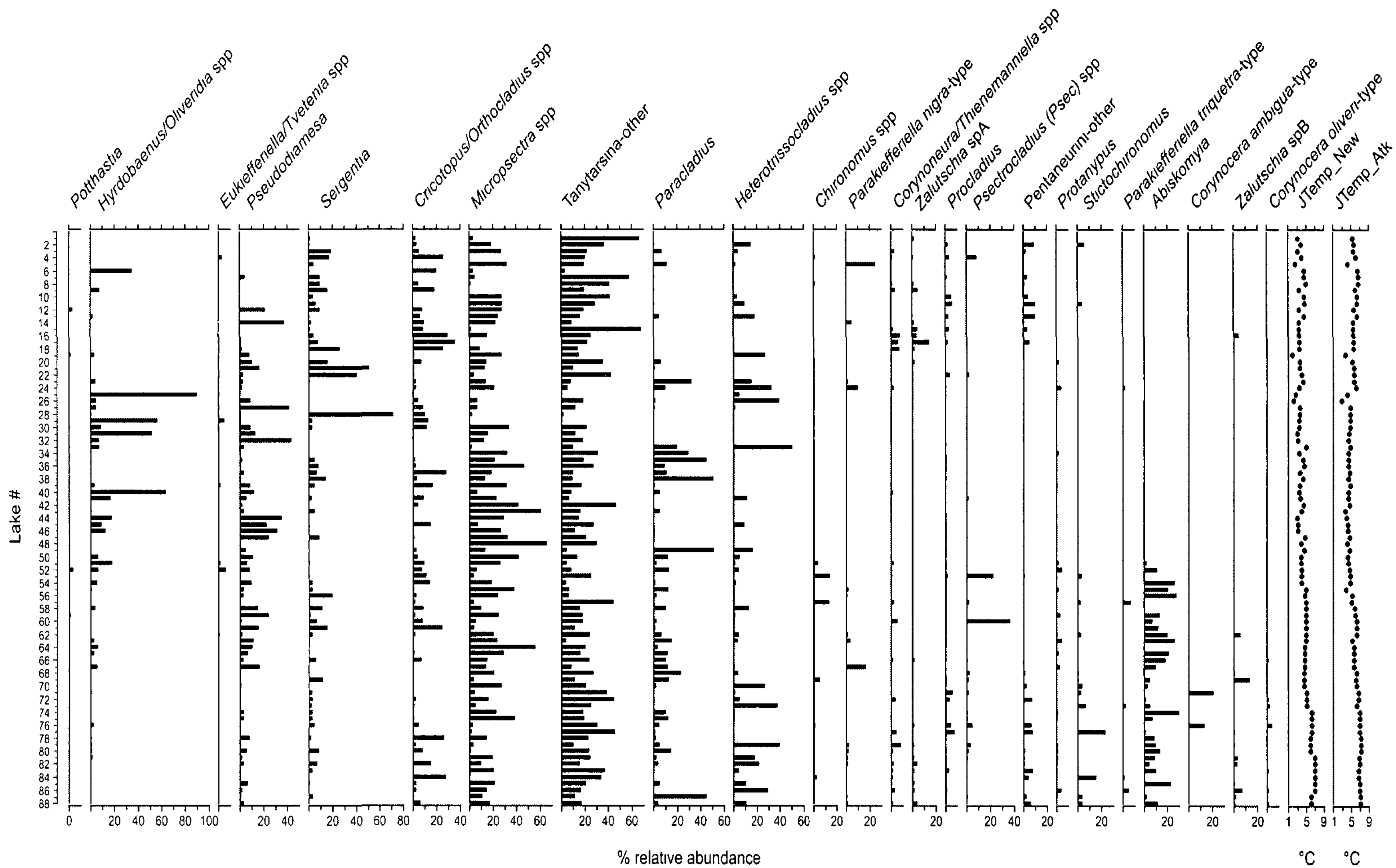

Figure 2 Chironomid relative abundances (%) for 88 lakes from the Canadian Arctic arranged according to their mean July air temperatures as extracted by the New et al. (2002) gridded data set (°C, $WA_{tol/class}$, bootstrapped). Only taxa with relative abundances ≥2% in two or more lakes are included. Mean July air temperatures as extracted from the New et al. (2002; JTemp_New) and Atkinson and Gajewski (2002; JTemp_Atk) (see text) are also presented

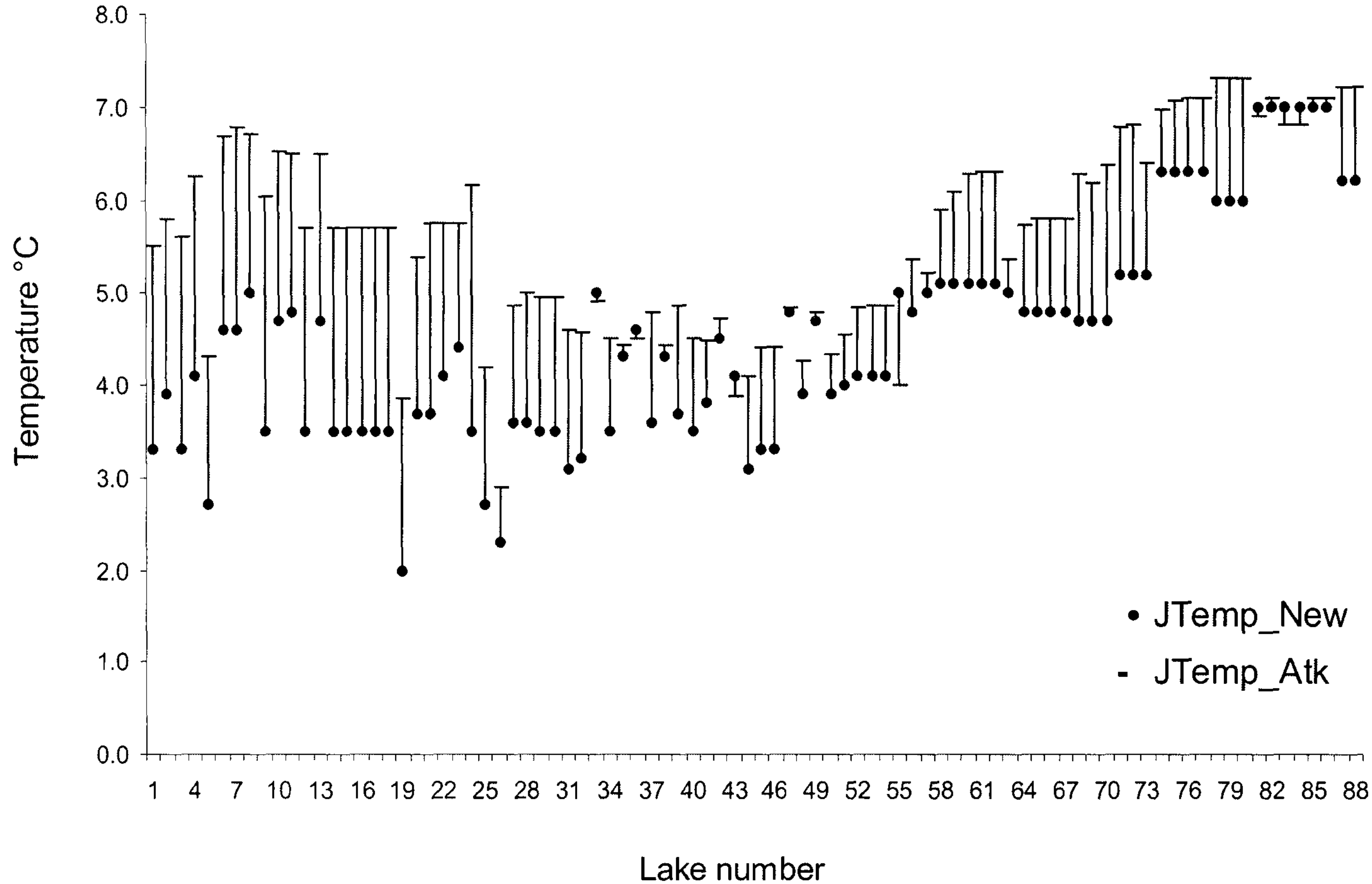

Figure 3 Mean July air temperatures extracted from the New et al. (2002) (•, JTemp_New) and from the Atkinson and Gajewski (2002) (–, JTemp_Atk) gridded data set for 88 lakes from the Canadian Arctic. Lakes are plotted according to decreasing latitude. Lake names are presented in Table 1

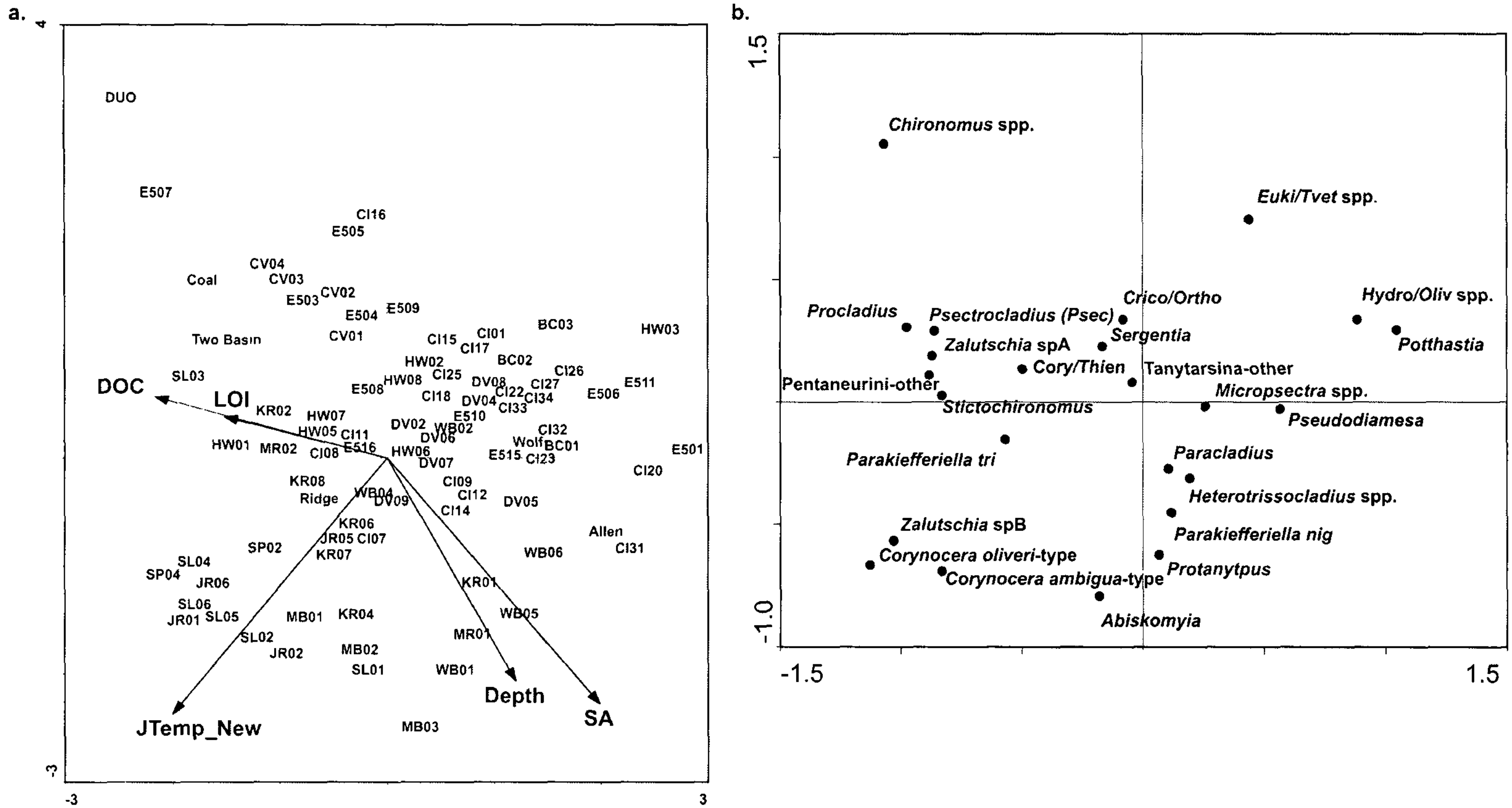

Figure 4 Canonical correspondence analysis (CCA) biplots of five important environmental variables in relation lakes (a) and to chironomid taxa (b) from the Canadian Arctic. Environmental data were transformed prior to use in the CCA and only taxa with relative abundances ≥2% in two or more lakes are included. JTemp_New extracted from New et al. (2002); DOC=dissolved organic carbon, LOI=sediment organic content as measured by loss-on-ignition at 550°C, SA=lake surface area, depth=lake depth; *Crico/Orth.=Cricotopus/Orthocladius* spp., *Parakiefferiella tri=Parakiefferiella triquetra*-type, *Parakiefferiella nig=Parakiefferiella nigra*-type *Euki/Tvet=Eukiefffieriella/Tvetenia* spp., *Hydro/Oliv=Hydrobaenus/Oliveridia* spp., *Psectrocladius (Psec)=Psectrocladius (Psectrocladius)* spp. and *Cory/Thien=Corynoneura/Thienemanniella* spp.

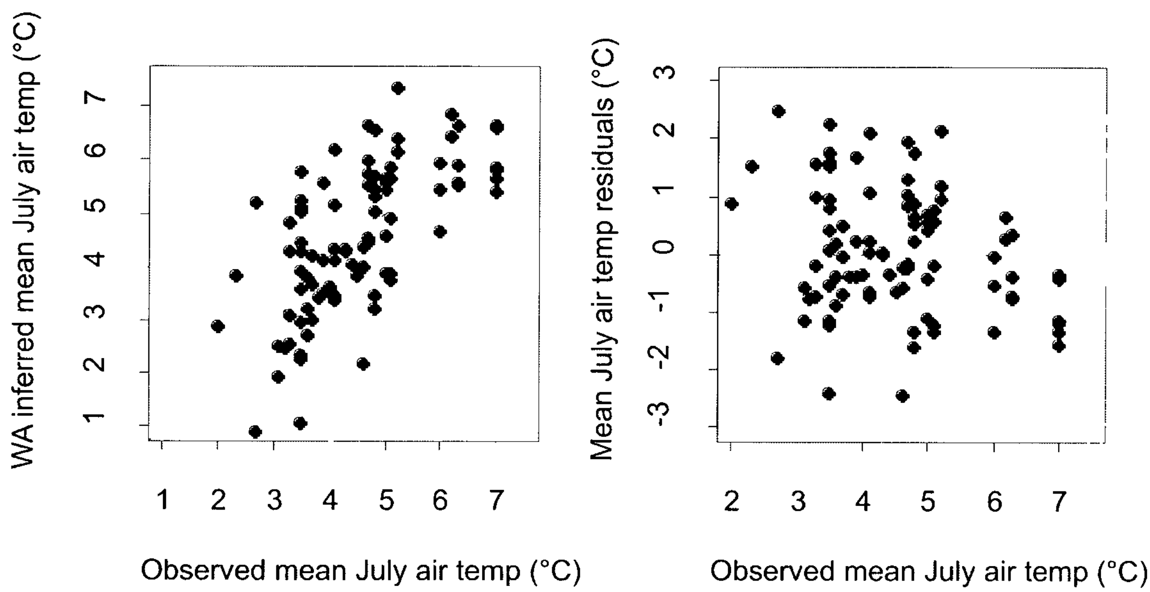

Figure 5 Scatterplots of the observed vs predicted JTemp_New, and residuals versus observed JTemp_New of a weighted average ($WA_{tol/class}$) model using three components, 1,000 cycle bootstrapping). JTemp_New extracted from New et al. (2002)

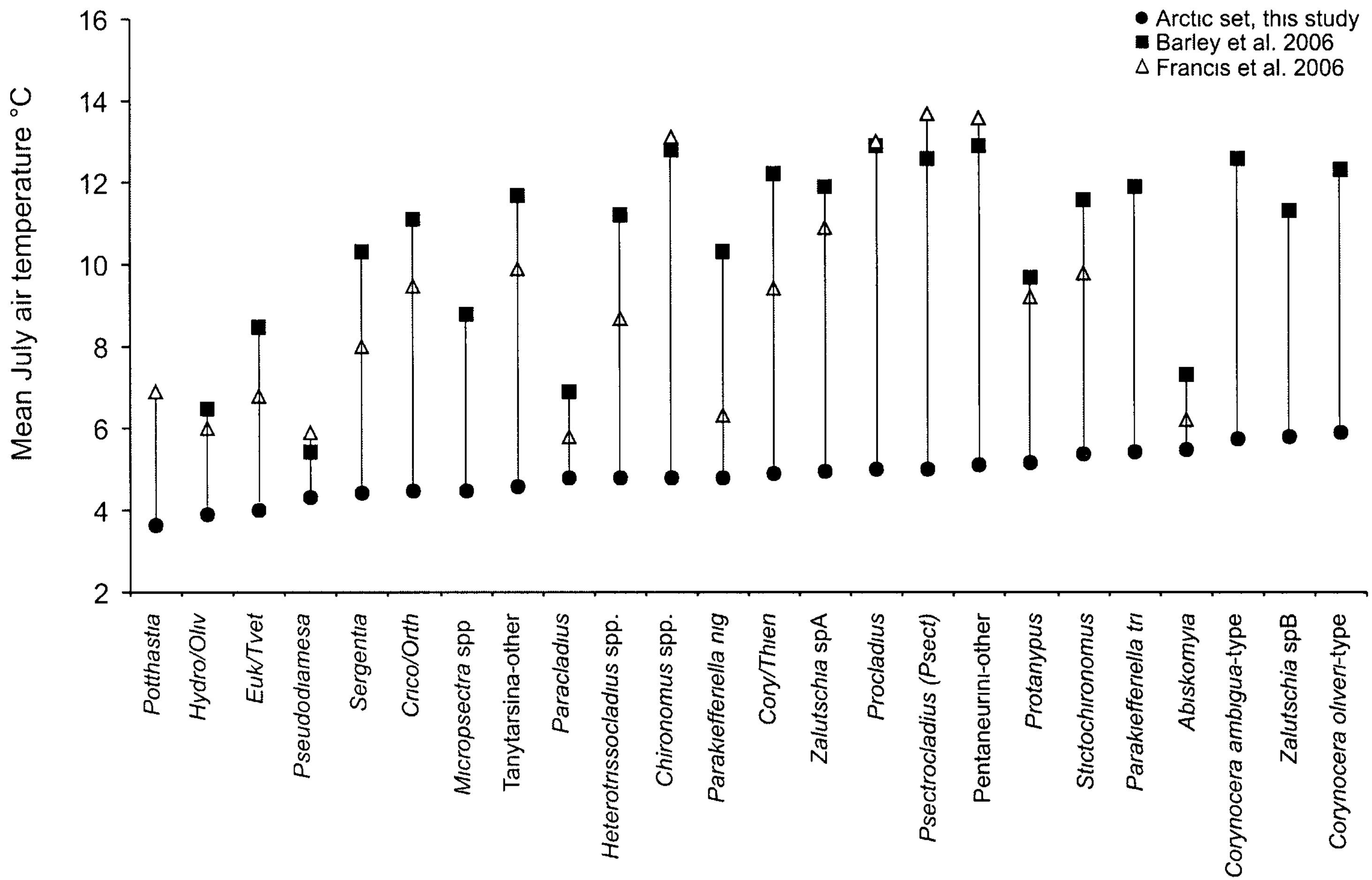

Figure 6 Mean July air temperature optima (°C) for chironomid taxa from the Canadian Arctic obtained from three studies: this study (Arctic set), Barley et al. (2006), and Francis et al. (2006). Taxa are ranked in order of increasing optimal JTemp_New as determined in this study. See caption of Figure 4 for taxa abbreviations

Chapter 4

Chironomid-environment relations in northern North America

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Keywords: Chironomid training set, North America, Boreal forest, Arctic, Weighted average partial least squares, Modern analogue method, Mean July air temperature, Inference model

Abstract

A chironomid based training set including 379 lakes from the Canadian Arctic and the Boreal regions was generated by combining 6 previously-published chironomid training sets from northern North America. The weighted average partial least squares model retaining 3 components provided the best performance statistics (r^2_{boot}= 0.73, $RMSEP_{boot}$= 1.93, maximum bias= 1.87°C). This new training set includes lakes that span a large July air temperature gradient (2°-16.6°C) and that contain a large diversity of chironomid assemblages. An inference model using weighted averaging partial least squares was developed for reconstructing past mean July air temperatures based on the chironomid fossil record in sediment cores. This training set is appropriate for use in reconstructions of past temperatures using the sediment from lakes in the Arctic and boreal regions.

Introduction

Reconstructing past temperatures or other environmental parameters based on the fossil record of a lake sediment core is often a primary objective of chironomid-based paleoenvironmental studies (Birks, 1998). These paleoenvironmental reconstructions are most useful when they can be quantified. To develop these quantitative estimates of the past, a calibration equation is developed based on modern conditions (Webb and Bryson, 1972). These are based on so-called "training sets", which is a spatial array of chironomid assemblages from the uppermost sediments of a series of lakes ("modern samples") and the matched measures of the environment (Birks, 1995). Regression or other techniques are used to develop predictive equations relating the biological and environmental (in most cases, temperature) parameters, and these equations can be used with fossil assemblages to estimate past environmental conditions.

The outcome of any paleolimnological environmental reconstruction is greatly dependent on the choices made in the creation and use of the fossil modern training set (e.g. ter Braak and Looman, 1986; ter Braak and Juggins, 1993; Birks, 1998; Lotter et al., 1999; Brooks and Birks, 2001; Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol 2001; Walker and Cwynar, 2006). Any biases present during creation of the training set and the choices made in the data analysis directly and greatly affect the resulting reconstructions. As a result, there is a large literature on the development and use of calibration equations in paleolimnology, and several different methods and approaches have been proposed (e.g. ter Braak and Looman, 1986; ter Braak and Juggins, 1993; ter Braak, 1995; Birks, 1998; Lotter et al., 1999; Brooks and Birks, 2001; Smol, 2002; Ko□ster et al. 2004; Telford et al., 2009)

Traditionally paleolimnologists have chosen to create a training set by crossing some sort of environmental or vegetation gradient (eg. Barley et al., 2006; Larocque et al., 2006;

Porinchu et al., 2009a). The rationale behind this strategy is the ecological idea that species-environment relations are most easily seen at ecotones, as the primary environmental factor that causes the ecotone would be most strongly expressed. These types of studies are often apparently successful, as the largest gradient captured in these types of analysis are given by the construct of the experimental design. Of course, in reality, ecological relations are rarely so simple. In particular, these studies typically span only part of the environmental range of the species, and thus the regressions are based on incomplete data (Birks, 1998).

An alternative is to collect data from a spatial array of lakes across the entire geographic expanse of the constituent taxa, for example the entire continent of North America (e.g., Whitmore et al., 2005). Response surfaces, in one or several dimensions, can be developed that depict the relation between the taxa and the environment, including interactions of several variables, across the entire range, and in this way depict the complexity of the species environment relation more accurately (e.g. ter Braak, 1995). Studies using this approach have higher success when applied to the distant past, when conditions may have been greatly different than the present.

Although palynologists have successfully developed extensive datasets spanning entire continents (Whitmore et al., 2005), paleolimnologists have tended to rely on small local datasets for calibration. For the study of chironomids, a number of these local training sets have been published, especially in northern North America (Walker et al., 1997; Wilson and Gajewski, 2004; Gajewski et al., 2005; Larocque et al., 2006; Porinchu et al., 2009a). In this study we have combined a number of datasets to create a chironomid calibration set for reconstructing past mean July air temperatures for the Arctic and Boreal North America. The motivation for this exercise comes from our previous studies reconstructing Holocene climates from the Arctic (Fortin and Gajewski, 2010a [5]; 2010b [6]). When attempting to use results from different published training sets, it became apparent that the species temperature optima estimated from the various studies were quite different, the down-core reconstruction derived from these different equations also differed, and that each training set could only provide limited good modern analogues for the fossil records (Fortin, 2010 [3]). In addition, it was difficult to know *a priori* which, if any of the training sets was the "best" to use for a particular core, and, indeed, all were found lacking in some aspect. The purpose of this paper is to present a more extensive calibration dataset, comprising samples from across all of northern North America in order to provide a calibration dataset that may be suitable for Arctic and subarctic paleoclimate studies.

Methods

This study is based on data previously presented in 6 modern chironomid studies from northern North America (Wilson and Gajewski, 2004; Gajewski et al., 2005; Barley et al., 2006, Larocque et al., 2006, Porinchu et al., 2009a, Fortin [3]). Data from these studies span the Arctic and Boreal regions of Canada and Alaska with the exception of the Baffin Island and Labrador (Table 1, Figure 1). Two chironomid-based studies from eastern Canada are not further considered here, as environmental data were not collected (Walker et al, 1997; Francis et al., 2006) and in any event, these data are not available.

Fortin [3] studied 91 lakes located across the entire Canadian Arctic Archipelago including data from Gajewski et al. (2005) incorporated after taxonomic harmonization (Barley et al., 2006). Porinchu et al. (2009a) studied a series of 88 lakes in a transect across the boreal/tundra zone from Victoria Island to the northern Northwest Territories mainland, and a comparable study of 60 sites across treeline in northern Québec was studied by Larocque et al. (2006). From the western boreal zone, 39 lakes from southwest Yukon and northern British Columbia were analyzed by Wilson and Gajewski (2004), to which Bunbury and Gajewski (2008) subsequently contributed two new sites. Barley et al. (2006) examined 145 lakes from southern British Columbia to the Yukon, Alaska and Tuktoyaktuk Peninsula. Barley et al. (2006) was a compilation of four independently-collected sets and as such, data for twenty-four Canadian Arctic lakes are present in both Fortin ([3]) and Barley et al. (2006). For this study, duplicate sites were removed, different units were reconciled and the taxonomies were harmonized before creation of the final data matrix.

Details regarding the sampling of the surface sediments and the collection of environmental data, as well as the sediment and chironomid head capsule (HC) analyses, can be found in the respective publications. In general, surface sediments were collected during the spring or summer, and from the deepest area of each lake using a Livingston piston corer, a Glew or a Kajak-Brinkhurst surface corer or an Ekman dredge. Only the top one to two centimeters of each sample was used in the analysis.

Because temperature was estimated using different methods in the 6 studies, mean July air temperatures were extracted for all lakes using the New et al. (2002) gridded climate data. The mean July air temperature from the nearest gridpoint to the location of the lake was extracted in a geographic information system (Gajewski, 2000a; Table 1). The use of a global temperature grid potentially introduces problems when reconstructing past climates in cores from Arctic areas (Fortin [3]), but this issue does not affect the results presented in this paper.

Chironomid head capsule identifications were performed by different analysts in each original study but were completed using the same basic reference material. Wilson and Gajewski (2004), which is the oldest study, has the coarsest identification resolution and principally follows Wiederholm (1983) and Oliver and Roussel (1983). Barley et al. (2006)

and Larocque et al. (2006) also based their identifications in part on these references and both studies provided a reference guide with head capsule (HC) images of their identifications (Barley, 2004; Larocque and Rolland, 2006). Fortin ([3]) and Porinchu et al. (2009a) used Wiederholm (1983) and Oliver and Roussel (1983) as well as Barley (2004), Larocque et al. (2006) and Brooks et al. (2007) identification keys.

The original studies used different minimum head capsule criteria, from 75 HC in Barley et al. (2006), to the more inclusive minimum of 35 HC and 38 HC in Fortin ([3]) and Porinchu et al. (2009a), respectively. Although 50 HC has been suggested as a minimum number per sample for use in calibration studies (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001), this criterion often leads to the removal of less productive, often colder lakes from the training sets, therefore biasing any reconstructions in Arctic regions (Fortin and Gajewski, 2010a [5]). We therefore retained a more conservative minimum of 35 HC for this study. A total of 379 lakes met this minimum head capsule criterion.

Data screening

Only environmental and limnological variables with fewer than 10% missing values (of the total number of lakes) and those with fewer than 50% of their values below detection limit were included in the statistical analyses. Missing values were replaced by the mean for the variable, and the midpoint between zero and the detection limit was used to replace values that were below detection. In the combined data set, only 12 environmental variables were retained. Transformations were performed on the variables which did not have normal distributions. Conductivity, lake depth, dissolved organic carbon (DOC), total unfiltered phosphorous (TP_{unf}), Cl, SiO_2, SO_4, Ca, Fe and K were all log transformed, whereas mean July air temperatures (JTemp) and pH did not require any transformation.

The chironomid identifications were harmonized (Appendix 3), mostly to correspond to the slightly coarser identification resolution of Wilson and Gajewski (2004). There were also some inconsistencies between training sets regarding the criteria used to identify the species within their respective *Cricotopus/Orthocladius* spp., *Heterotrissocladius* spp., Micropsectra spp. and *Zalutschia* spp. groups, and as a result these species were combined prior to analysis. This resulted in total of 82 taxa, with very few identified to the species level (e.g., *Cornynocera ambigua*-type, *Zalutschia zalutschicola*). Most taxa remained identified at the genus level. Combining taxa below the sub-tribe Tanytarsina-other and tribe level Pentaneurini-other was also necessary. All chironomid data used in the analyses are relative abundances, with rare taxa and unknown chironomids included in the final percentage calculations. Only taxa whose relative abundances were ≥2% in two or more lakes were included (Fortin [3]), leaving 58 taxa for the subsequent analysis.

Ordination analysis

All ordination analyses were performed using CANOCO (ter Braak and Šmilauer, 2002). A detrended canonical analysis (DCA) was first performed on the species data (detrending by linear segments) and based on the length of the gradient (3.644 S.D. units and 2.930 S.D. units for the 1st and 2nd axes) unimodal models were used for the remainder of the analysis (Hill and Gauch, 1980; ter Braak and Šmilauer, 2002). Canonical correspondence analysis (CCA) and partial CCAs were then used to relate environmental to chironomid data.

Temperature reconstruction

Mean July air temperature (JTemp) inference models were developed using partial least squares (PLS), weighted average (WA) and weighted average partial least squares regressions (WAPLS) (Juggins, 2003). Species data were square-root transformed, and models were cross-validated using bootstrapping (1,000 times). Criteria for model selection included maximizing r^2_{boot} and minimizing the maximum bias (max_bias_{boot}) and root mean squared error of prediction ($RMSEP_{boot}$). Scatterplots of the observed vs inferred JTemp and a residual plot were also used.

Results

After removing duplicates and lakes with missing environmental information, data from 379 lakes were available. Lakes ranged from northern Ellesmere Island to the British Columbia border in the south, and from Alaska to northern Québec. Sites were available from the polar desert, mid and low arctic tundra, as well as sites from the boreal forest and forest tundra. In general, lake waters were cold and oligotrophic, with low conductivities and relatively high pH (Table 1). Although the boreal forest and tundra are both wide-ranging circumpolar ecosystems, there are regional differences in the climate and physical environment within these vegetation zones that impact lake conditions and water chemistry. For example the boreal forest of northern Québec (Larocque et al., 2006) is relatively moist but the southwest Yukon (Wilson and Gajewski, 2004) is very dry and this will impact the water balance and thereby nutrient and chemical balance of the lakes.

Major chironomid taxa in the training set include the taxonomically larger groups such as Tanytarsina-other, *Micropsectra* spp, *Heterotrissocladius* spp., *Psectrocladius* (*Psectrocladius*) spp. and *Cricotopus*/*Orthocladius* spp. These taxa are present in lakes from all regions with the exception of *Psectrocladius (Psectrocladius)* which is only sporadically present in the Arctic Islands, mostly in Victoria Island lakes. Taxa from the subtribe Chironomini are more abundant in lakes from the mainland and are generally excluded from the tundra regions of the Canadian Arctic Islands, with the exception of *Chironomus* spp. and *Sergentia* spp. which were widely distributed. *Abiskomyia*, which is almost exclusively found in the Arctic is also present in a few lakes in the Northwest territories (central and Tuktoyaktuk region) and Alaska, dispelling the notion that this taxon is geographically limited only to the Arctic Archipelago (Wilson and Gajewski, 2004; Fortin [3]).

Based on an exploratory data analysis, it was not necessary to remove any of the 379 lakes prior to the ordination analyses. Lakes that had been considered to be significant outliers in their respective studies were no longer considered as such in the combined dataset, since the diversity of species assemblages had significantly increased from combining the training sets. This suggests that the outliers previously identified were not "problems" or "errors", but rather appeared as such due to an insufficient sampling of the total population.

Ordination

Canonical correspondence analyses (CCAs) constrained to each environmental variable separately (excluding latitude, longitude and distance from coast) were first performed with Monte Carlo permutations (499) to determine the marginal effect of each of these variables. This step determined that all 12 environmental variables (JTemp, depth, pH, Conductivity, DOC, TP_{un}, Cl, SiO_2, SO_4, Ca, Fe and K) were significantly correlated with chironomid distributions. A series of CCAs using these significant variables ($p<0.05$) was performed, and leverage diagnostics were examined to determine if a particular environmental variable caused certain lakes to be considered as outliers. Although all environmental variables had inflation factors of <10, the leverage diagnostics identified seven lakes as outliers based solely on their K content. As it is important to keep as many lakes as possible in the training set, K was removed from the analysis. Furthermore, lakes KW03 and AK07 were considered as outliers with respect to only TP_{unf} but were nonetheless retained in the analysis.

A final CCA with forward selection of the 12 significant variables was then used to determine the subset of environmental variables that together explain a significant portion of the variation in species data. As no two environmental variables were significantly correlated, all remaining 11 variables significantly contributed to explaining the chironomid distribution. The species variance explained by the first two axes of the CCAs constrained to the 11 environmental variables was low (13.6%; with λ_1=0.316, λ_2=0.103) indicating that much unexplained variance in the taxa assemblage data still remains (Table 2).

The significance of the first two axes for this final CCA (which included all 11 significant environmental variables) was confirmed using Monte Carlo permutations (499) ($p \leq 0.001$), and the relationship between these axes and the significant environmental variables were evaluated using canonical coefficients, t-values, and inter- and intra-set correlations (Table 3). All 11 variables were significantly correlated with one or both of the axes. CCA axis 1 was significantly related to JTemp, depth and DOC (-0.78, 0.48, -0.31 respectively) whereas axis 2 was significantly correlated to conductivity, Ca and pH (0.54, -0.36, 0.35). These findings, based on the canonical coefficients and t-values, were confirmed by the inter- and intra-set correlations.

A biplot of the CCA results summarizes the differences as well as similarities among the chironomid communities and environments of northern Canada and Alaska (Figure 2a). Sites from the boreal forest had the warmest temperatures (Barley et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a) as expected. In western Canada and Alaska, lakes differ in their TP_{unf} values (Wilson and Gajewski, 2004; Barley et al., 2006). Samples from the treeline areas of eastern, central and western Canada and Alaska (Barley et al., 2006;

Larocque et al., 2006; Porinchu et al., 2009a) show considerable similarity in chironomid assemblages and environmental conditions, as indicated by the "overlap" in the ordination plot. There is less similarly between samples from northern Québec (Barley et al., 2006) and those from the southwest Yukon (Wilson and Gajewski, 2004); these two regions come from respectively the wettest and driest of the regions under study.

The distance between samples (lakes) on a biplot can be used as an indication of species turnover (as measured in standard deviation units; S.D.), with lakes 4 S.D. apart having very little probability of sharing any species (Lepš and Šmilauer, 2003). The Arctic sites (Fortin [3]) all ordinate on the right side of the diagram, indicating that these lakes are generally colder, less productive and deeper than those from the other regions. The more northerly samples from the Arctic have distinct species assemblages from most of the other lakes in the dataset, with the exception of some of the more northern lakes from Victoria Island (Porinchu et al., 2009a). The chironomid communities and environments of the high- and mid-Arctic regions can therefore be numerically distinguished from the tundra and forest samples.

The taxa ordinate on a biplot according to their environmental preferences (Figure 2b). Chironomid taxa on the far left of the biplot, such as *Microtendipes* spp., *Pagastiella* and *Cryptotendipes* all prefer warmer conditions, whereas *Lubrundinia*, *Derotanypus*, *Chironomus* spp. and *Pseudochironomus* prefer the warmer lakes with higher nutrients and DOC content. The colder tolerant taxa are *Potthastia*, *Pseudodiamesa*, *Abiskomyia*, *Hydrobaenus/Oliveridia* spp. and *Paracladius,* whereas *Micropsectra* spp., *Heterotrissocladius* spp. and *Protanypus* prefer deeper lakes. *Paracladopelma*, *Constempellina* and *Heterotanytarsus* can be found in more acidic conditions.

Transfer function development and environmental reconstructions

Chironomid-based transfer functions were developed for reconstructing mean July air temperature as this is often a variable of interest for paleoenvironmental reconstructions and it was determined to be significantly related to chironomid distributions. A DCA performed on the species data indicated that unimodal statistics, such as weighted averaging (WA) and weighted averaging with tolerance downweighting (WA_{tol}) and weighted averaging partial least square (WAPLS) were appropriate for developing inference models (Table 4). A partial least square model (PLS) was also developed for comparative purposes.

A WAPLS model (including 3 components) generated the most robust reconstruction, with the highest r^2_{boot}, lowest $RMSEP_{boot}$ and lowest maximum bias of all other models (Table 4). The WAPLS component 3 was chosen over the more parsimonious component 2, as the scatterplot of the observed versus reconstructed mean July air temperature and the residuals keeping 3 components showed less of a bias. The residual scatterplots based on the WAPLS (3 component) model indicated some underestimation of high values, as is often seen when using weighted averaging inference techniques (ter Braak and Juggins, 1993; Birks, 1998) (Figure 3).

Species tolerance and optima were generated by the WA model (Table 5). Based on the range of July air temperatures included in this model (2°C-16.6°C), *Pseudodiamesa*, *Potthastia*, *Hydrobaenus/Oliveridia* spp. and *Paracladius* had the coldest temperature optima (4.4; 4.5; 5.7 and 6.0°C, respectively), whereas *Pseudochironomus*, *Cryptotendipes*, *Lauterborniella/Zavrelliella* spp. and *Labrundinia* preferred warmer conditions (JTemp optima 13.4; 13.5; 13.9 and 14.4°C, respectively).

Discussion

Chironomid distribution and abundance are affected by many factors including temperature, lake morphometry and food supply. In this study, the relation of July air temperature to chironomid assemblages was strong enough that a transfer function could be derived. Lake morphometry is often identified as an influential variable on chironomid assemblages (e.g. Walker et al., 1991; Hofmann et al., 1998; Gajewski et al., 2005; Barley et al., 2006; Porinchu et al., 2009a). This was also the case in this study, where lake depth was significantly related to changes in chironomid composition. Factors related to lake bedrock composition (as inferred from the significance of lake water pH, conductivity and Ca), which affect nutrient levels, and lake production also played a significant role in the chironomid distribution (Fortin and Gajewski, 2009 [2]). The importance of organic matter on the distribution of the chironomids however could not be assessed as loss-on-ignition (LOI) was not available for all samples. Dissolved organic carbon and SiO_2 were shown to be important, and these are correlated with sediment organic content (as measured by loss-on-ignition at 550°C) in Arctic lakes and may indicate the importance of food supply on chironomids in the region (Fortin and Gajewski, 2009 [2]).

A weighted averaging partial least squares (WAPLS; 3 component) inference model was generated that can be used to derive past mean July air temperatures from chironomid fossil records. The overall performance of this model is quite strong, with a relatively high r^2_{boot} and low max $bias_{boot}$ and $RMSEP_{boot}$; these results are comparable to the performance statistics of other chironomid-based summer temperature inference models from the region (Walker et al., 1997; Barley et al., 2006; Francis et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a). A slight bias is present in the model, which can lead to underestimating higher July air temperatures and overestimating cold conditions, as also seen in the equation derived by Barley et al. (2006). However, the larger gradient covered in the present study will result in a better estimation of July air temperatures for a greater range of past conditions.

This training set generated by this study not only covers a large temperature range, but also contains a higher density (higher number) of sites within this range. These two factors increase the likelihood, in a paleoenvironmental analysis, of finding a number of close modern analogues to the downcore fossil data. In the Canadian north, for example, there is evidence that it was much warmer in the early Holocene than today, although the degree of this increase in temperature is uncertain (Kauffman et al., 2004). Therefore to accurately reconstruct early Holocene temperatures for a site in the Arctic or to find analogues for fossil assemblages from a sediment core, the modern data would need to contain lakes with temperatures warmer than the modern temperatures in the immediate region of the paleoreconstruction study site. For this reason, transfer functions based on samples from a small local area are inadequate for paleoclimate analyses. Our transfer function is based on a wide July air temperature range and therefore has a greater chance of adequately representing these warmer early Holocene conditions than would a more geographically restricted training set. The other advantage of this larger training set over the smaller training sets is the greater density of sites across the area than in previous studies, especially in the high-Arctic. A reconstruction based on a modern analogue technique is more likely to be robust if the downcore fossil assemblages are extensively represented in the modern training set (Birks and Birks, 1980). For example, Fortin and Gajewski, (2010a [5]) showed that previous calibration equations were not based on a sufficient number of sites from the cold high-Arctic, and thus provided puzzling reconstructions that can now be reconciled through the use of this new dataset. The large diversity and density of sites and species assemblage in the modern data set allows this calibration equation to be used to reconstruct a wider range of past temperatures for a larger number of sites across the continent.

There are large differences in the estimates of the mean July air temperature optima for the various taxa generated by the different training sets (using their original temperature measurements) as illustrated in Fortin [3]. This is because previous studies only contained a portion of the temperature gradient of each chironomid taxon (ter Braak and Looman, 1986). The WA model cannot properly estimate the optimum or tolerance when there are insufficient samples across the full gradient in which the taxa is present. Although it is difficult to determine what the complete gradient is for any taxon, combining training sets and thus increasing the overall range of temperatures would maximise the probability of capturing the largest possible portion of the taxa's distribution. In addition, a larger number of samples will increase the probability of encountering rare taxa in higher numbers, thereby permitting the estimation of the model parameters for these taxa.

The harmonization of taxonomies used in different studies often leads to the combining of taxa into higher order groups (Birks, 1998; Lotter et al., 1999; Walker and Cwynar, 2006). Combining species level identifications into higher level groups is traditionally not considered desirable, as each species should have a different niche from others, and information regarding species level environmental preferences is lost (Brooks and Birks, 2001). For example, Laroque et al. (2006) and Porinchu et al. (2009a) were able to differentiate between a number of taxa now combined in the Tanytarsina and *Micropsectra* groups, and showed that species from these groups do in fact have different environmental preferences. This problem is likely also true for the taxa that are combined in the *Heterotrissocladius* and *Cricotopus/Orthocladius* groups. Compounding this issue in Arctic studies is that Tanytarsina, *Micropsectra*, *Heterotrissocladius* and *Cricotopus/Orthocladius* groups are often the most abundant in the assemblages. This means that some resolution in defining the taxon-environment relation may be lost. On the other hand, it may be possible to more accurately estimate statistical parameters when numbers of head capsules are higher, as is found when lower level taxa are summed. Different species of a higher taxonomic group may not be overly functionally different; insight into ecological or biogeographic patterns can, in any event, be obtained at many taxonomic levels. In any event combining taxa resolves identification discrepancies that still exist between research groups notably when identifying chironomid fossils to the species level.

Conclusion

In this study, 6 previously published training sets, comprising 379 lakes, were combined to provide a transfer function appropriate for paleoenvironmental reconstructions in both Boreal and Arctic regions. A weighted average partial least square inference model for deriving past mean July air temperatures from the fossil chironomid assemblages was developed (r^2_{boot}= 0.73, RMSEP $_{boot}$= 1.93°C, maximum bias= 1.87°C). As this training set contains a greater diversity of chironomid assemblages and covers a large range of mean July air temperatures, it is likely to contain not only a large number of modern analogues for the downcore fossil data from both Arctic and Boreal lakes but is also likely to accurately estimate a potentially wider range of past mean July air temperatures than would more regional training sets.

Table 1 Statistical summary of the physical, environmental, and limnological parameters for lakes used in this study. Depth is water depth to sediment at the coring site, Cond is conductivity, JTemp is mean July air temperature extracted from New et al. (2002), DOC is dissolved organic carbon, TP_{unf} is total phosphorous unfiltered. The --- denotes where data are missing. SD= standard deviation units. There is some overlap in sites between training sets affecting the overall number of lakes in the combined training set

Publication	Geographical location	Number of lakes		Depth m	Cond µS cm^{1}	JTemp °C	pH	DOC mg l^{1}	TP_{unf} mg l^{1}	Cl mg l^{1}	SiO_2 mgl^{1}	SO_4 mg l^{1}	Ca mg l^{1}	Fe mg l-1	K mg l^{1}
Wilson & Gajewski	Western Yukon	41	Mean	5 2	382	11 3	8 6	11 9	0 014	2 7	3 139	55 4	31 59	0 059	4 111
2004			SD	4 6	263	1 4	0 4	10 1	0 013	4 8	2 043	98 9	21 19	0 062	3 557
Gajewski et al	Arctic Islands	50	Mean	5 8	134	5 4	7 9	2 3	0 009	8 7	0 571	16 9	22 16	----	0 653
2005			SD	3 3	174	0 9	0 4	2 5	0 011	30 0	0 563	56 1	21 84	----	1 004
Barley et al	Alaska, BC, Yukon, NWT	121	Mean	7 5	113	12 6	7 9	17 7	0 030	4 0	3 210	9 0	17 17	0 163	1 236
2006			SD	7 3	93	3 3	0 6	32 7	0 147	8 2	4 059	13 4	13 02	0 254	2 335
Larocque et al	Northern Quebec	59	Mean	4 2	29	11 5	6 7	7 9	0 012	5 0	1 550	3 5	1 98	0 267	0 302
2006			SD	3 9	23	2 4	0 6	4 1	0 008	7 2	1 532	1 5	1 42	0 256	0 205
Porinchu et al	South Victoria Isl, NWT	88	Mean	3 2	82	9 3	7 3	9 2	0 010	6 2	0 596	3 2	10 23	0 214	0 663
2009			SD	2 3	70	2 2	1 0	18 2	0 007	11 1	0 595	4 9	9 69	0 467	0 438
Fortin [3]	Canadian Arctic Islands	92	Mean	7 3	131	4 5	7 7	2 2	0 009	7 2	0 555	15 6	19 99	0 055	0 759
			SD	6 0	182	1 2	0 6	2 3	0 011	25 7	0 556	47 2	20 64	0 116	1 383
This study	All sites	379	Mean	5 8	128	9 8	7 6	10 4	0 017	5 2	1 808	13 8	15 96	0 158	1 172
			SD	5 8	165	3 6	0 9	21 3	0 083	14 5	2 753	42 9	16 92	0 289	2 140

Table 2 Summary statistics of the DCA and CCA using only taxa present in ≥2% in two or more lakes (58 taxa). Included are the 11 significant environmental variables and the added variance they each explain as identified through forward selection in CCA. SD= standard deviation units, λ= eigenvalue. All λ $p<0.05$

DCA		Gradient length (SD)
axis 1		3.644
axis 2		2.930
CCA with all 11 significant variables		
	Variable	Added variance
1	JTemp	0.252
2	Depth	0.092
3	pH	0.08
4	DOC	0.021
5	TP_{unf}	0.02
6	Fe	0.019
7	$Si0_2$	0.019
8	Cl	0.017
9	Ca	0.017
10	SO_4	0.014
11	Cond	0.013
Total species variance explained by 11 variables		0.564
Total inertia		3.081
	λ1	0.316
	λ2	0.103
Cumulative % variance		
	taxon axis 1	10.26
	taxon axis 2	13.60
CCA constrained to JTemp		
λ1/λ2		1.08

Table 3 Canonical coefficients with t-values and inter- and intra- set correlations for the first 2 axes in a CCA, using taxa with abundance ≥2% in two or more lakes * p<0 05

	Canonical coefficient		tval				Inter-set correlation		Intra-set correlation	
	Axis 1	Axis 2	Axis 1		Axis 2		Axis 1	Axis 2	Axis 1	Axis 2
JTemp	-0 78	-0 09	-14 35	*	-1 31		-0 7677	-0 1191	-0 875	-0 1522
Depth	0 48	-0 20	11 52	*	-3 81	*	0 4019	-0 0959	0 4581	-0 1225
pH	-0 07	0 35	-1 29		4 74	*	-0 0004	0 6577	-0 0005	0 8406
DOC	-0 31	0 02	-5 67	*	0 35		-0 7083	0 0502	-0 8073	0 0641
TP_{unf}	-0 04	0 27	-0 81		4 75	*	-0 4432	0 1796	-0 5051	0 2296
Fe	0 11	-0 05	2 07	*	-0 74		-0 3567	-0 2013	-0 4065	-0 2572
SiO_2	-0 18	-0 24	-3 73	*	-4 01	*	-0 3695	0 0336	-0 4211	0 0429
Cl	-0 03	-0 36	-0 65		-6 24	*	-0 0701	0 0124	-0 0799	0 0158
Ca	0 17	0 41	2 04	*	3 73	*	0 0332	0 5983	0 0379	0 7647
SO_4	0 06	-0 32	1 27		-5 70	*	-0 1211	0 0666	-0 138	0 0852
Cond	-0 10	0 54	-1 01		4 24	*	-0 0641	0 5595	-0 073	0 7151

Table 4 Performance statistics of the inference models for reconstructing mean July air temperatures (JTemp). Only taxa with relative abundances ≥2% in 2 or more lakes were included in the analysis. r^2=coefficient of determination, RMSE=root mean square error and RMSEP=root mean square error of prediction. A 1000 cycle bootstrapping was performed. For details and abbreviations see methods section

Model		Apparent			Bootstrapped		
		r^2	RMSE °C	Max bias °C	r^2	RMSEP °C	Max bias °C
WA	Inverse	0.66	2.08	2.92	0.65	2.13	2.99
	Classical	0.66	2.57	2.18	0.65	2.59	1.95
WA_{tol}	Inverse	0.70	1.97	2.79	0.68	2.06	2.76
	Classical	0.70	2.36	1.80	0.68	2.43	1.80
WAPLS	1 component	0.66	2.09	2.76	0.65	2.14	2.84
	2 components	0.76	1.74	1.98	0.73	1.93	2.19
	3 components	0.78	1.66	1.65	0.73	1.93	1.87
	4 components	0.80	1.61	1.74	0.72	2.00	1.99
	5 components	0.80	1.60	1.65	0.72	2.03	1.94
PLS	1 component	0.55	2.40	3.33	0.54	2.44	3.41
	2 components	0.69	1.99	2.97	0.66	2.10	3.14
	3 components	0.73	1.85	2.32	0.69	2.03	2.56
	4 components	0.75	1.78	2.00	0.70	2.04	2.33
	5 components	0.76	1.75	1.84	0.70	2.06	2.23

Table 5 Weighted-averaging (WA) derived mean July air temperature optima and tolerance (bootstrapped) and Hill's N2 for all chironomid taxa present with abundance ≥2% in two or more lakes. Taxon numbers presented in this table are those used in Figure 2b. *Psectrocladius* (*Allo*/*Meso*)=*Psectrocladius* (*Allopsectrocladius*/*Mesopsectrocladius*) spp.

Code	Taxon	Hill's N2	$JTemp_{boot}$ °C Optima	Tolerance
1	*Pseudodiamesa*	49.5	4.4	1.5
2	*Potthastia*	6.5	4.6	2.1
3	*Hydrobaenus*/*Oliveridia* spp.	51.9	5.7	3.1
4	*Paracladius*	62.5	6.0	2.6
5	*Abiskomyia*	34.6	6.3	2.1
6	*Micropsectra* spp.	173.2	7.9	3.7
7	*Sergentia* spp.	151.3	8.8	3.6
8	*Eukieffferiella*/*Tvetenia* spp.	20.1	8.9	3.9
9	*Stictochironomus* spp.	64.2	9.1	2.9
10	*Protanytpus*	66.5	9.1	3.3
11	*Heterotrissocladius* spp.	133.2	9.4	3.2
12	*Cricotopus*/*Orthocladius* spp.	244.6	9.4	3.6
13	Tanytarsina-other	351.0	9.9	3.5
14	*Corynoneura*/*Thienemanniella* spp.	138.7	9.9	3.5
15	*Omisus*	6.4	10.1	1.3
16	*Corynocera oliveri*-type	82.6	10.1	2.4
17	*Zalutschia* spp.	141.0	10.2	3.0
18	*Parakiefferiella* spp.	103.9	10.4	3.3
19	*Paracricotopus*	7.5	10.5	1.1
20	*Limnophyes*	71.9	10.6	2.8
21	*Psectrocladius* (*Psectrocladius*) spp.	229.1	10.7	2.8
22	*Corynocera ambigua*-type	62.5	10.7	2.2
23	*Pseudosmittia*/*Smittia* spp.	11.6	10.7	3.4
24	Pentaneurini-other	178.1	10.8	3.1
25	*Georthocladius* spp.	4.5	10.9	2.4
26	*Mesocricotopus*	22.0	11.0	2.3
27	*Cladotanytarsus* spp.	79.3	11.0	2.4
28	*Procladius*	232.9	11.1	2.8
29	*Ablabesmyia*	28.0	11.2	2.3
30	*Thienemannimyia* spp.	22.5	11.2	2.4
31	*Monodiamesa*	15.1	11.2	2.1
32	*Chironomus* spp.	160.6	11.3	2.7
33	*Dicrotendipes* spp.	156.5	11.7	2.4
34	*Cladopelma* spp.	117.8	11.7	2.2
35	*Psectrocladius* (*Allo*/*Meso*) spp.	40.4	11.7	2.5
36	*Paracladopelma*	11.1	11.9	2.1

37	*Constempellina*	18.1	11.9	2.3
38	*Psectrocladius* (*Monopsectrocladius*) spp.	62.8	12.0	2.0
39	*Parachironomus* spp.	29.7	12.2	1.9
40	*Derotanypus*	11.4	12.3	1.3
41	*Stempellinella*/*Zavrelia* spp.	101.4	12.3	1.9
42	*Nanocladius* spp.	44.6	12.4	2.0
43	*Pagastiella*	62.4	12.4	1.9
44	*Einfeldia* spp.	15.4	12.5	2.2
45	*Parametriocnemus*/*Paraphaenocladius* spp.	22.0	12.5	2.8
46	*Zalutschia zalutschicola*	23.6	12.5	1.8
47	*Microtendipes* spp.	115.8	12.6	1.7
48	*Polypedilum* spp.	107.7	12.6	1.8
49	*Endochironomus* spp.	47.5	12.6	2.2
50	*Glyptotendipes* spp.	41.2	12.8	1.9
51	*Synorthocladius*	8.6	12.9	1.7
52	*Stempellina*	11.6	12.9	1.6
53	*Cryptotendipes*	51.9	13.0	1.5
54	*Heterotanytarsus*	30.2	13.1	1.6
55	*Pseudochironomus*	15.0	13.4	1.5
56	*Cryptochironomus*	26.2	13.5	1.3
57	*Lauterborniella*/*Zavreliella* spp.	5.5	13.9	1.1
58	*Labrundinia*	9.9	14.4	0.9

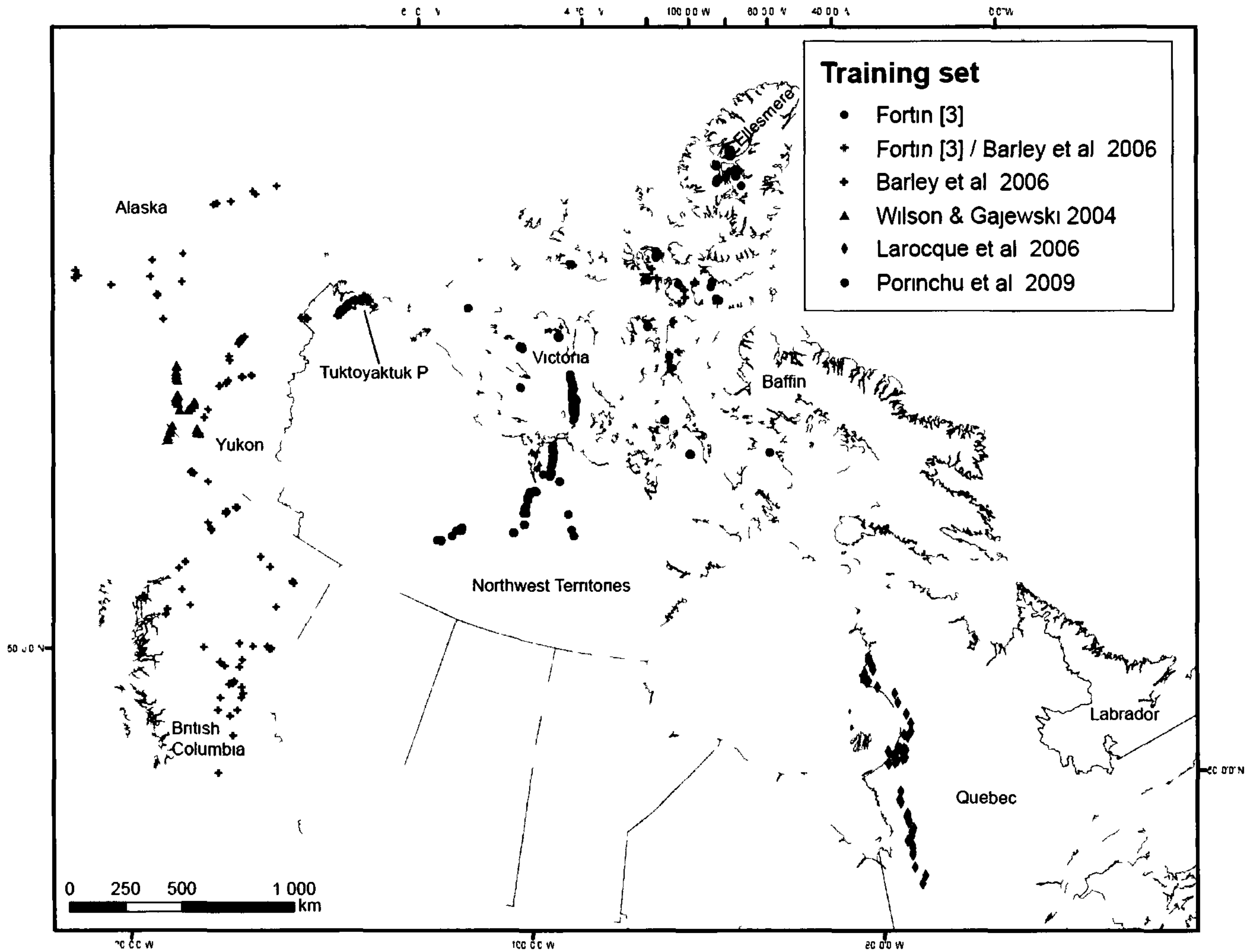

Figure 1 Location of sites from which chironomid data were obtained for the northern North American chironomid training set The sites identified with brown plus symbols are those which are included in both the Barley et al (2006) and Fortin [3] training set These sites, and 26 others from the Fortin [3] training set were originally from the Gajewski et al (2005) study (not specifically identified on map)

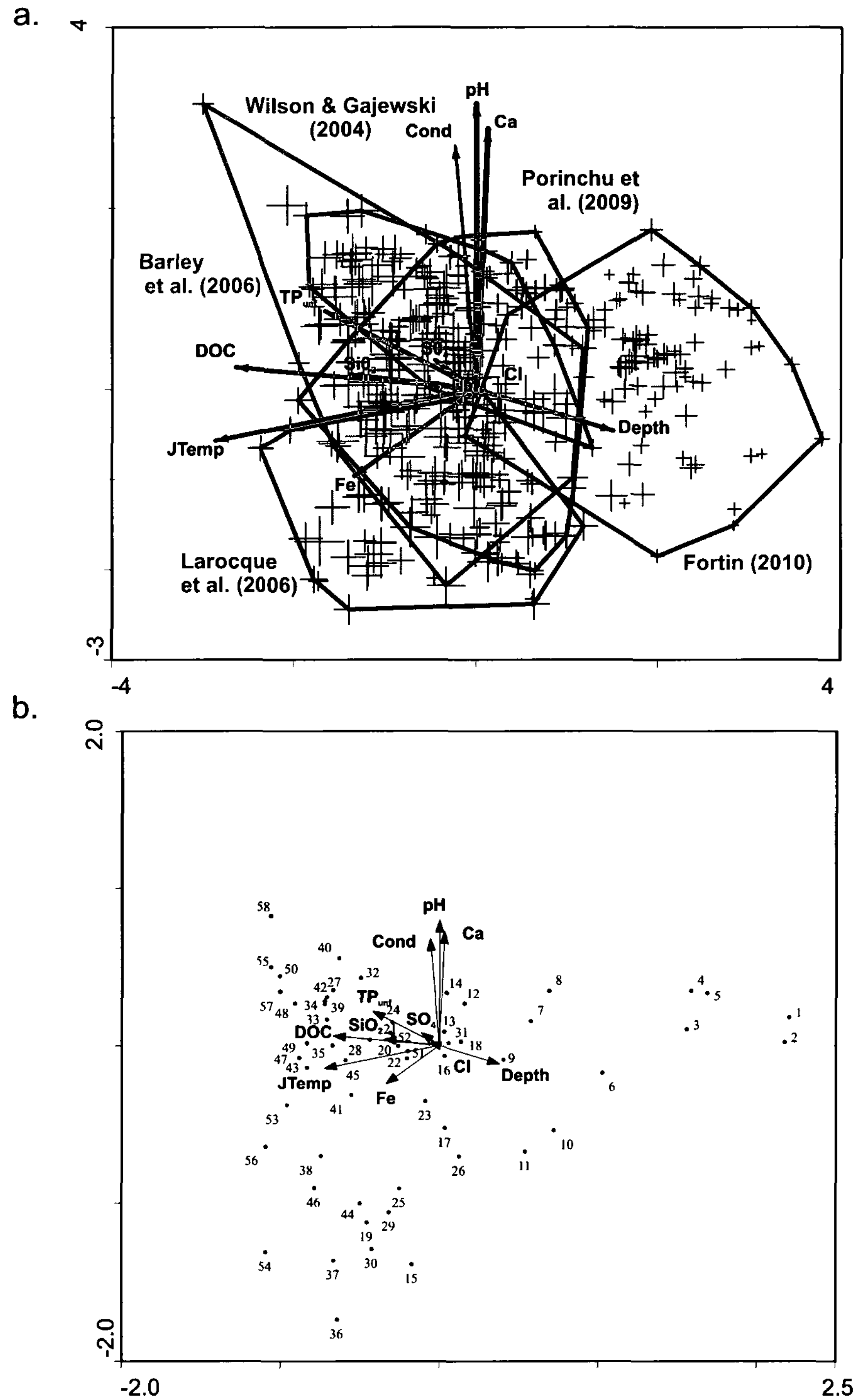

Figure 2 Canonical correspondence analysis (CCA) biplots of the a) 379 lakes and b) 58 chironomid taxa with the 11 environmental variables. In a) lakes belonging to the same original study are delimited by a convex hull. Cross sizes are proportional to the number of taxa in each sample (lake), with larger crosses indicating greater number of taxa The numbers in b) correspond to the taxa code in Table 5. Environmental data was transformed prior to use in the CCA . Fortin (2010) refers to Chapter 3 of this thesis

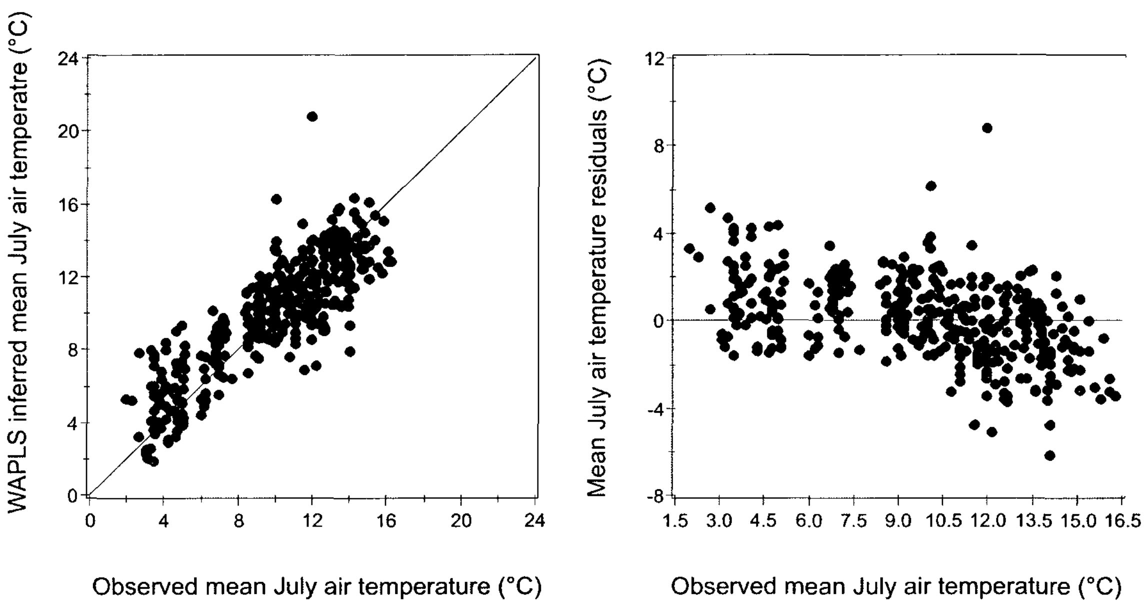

Figure 3 Scatterplots of the inferred vs observed July air temperatures and residuals of the weighted averaging partial least squared (WAPLS retaining 3 components, 1000 cycle bootstrapping) model *vs* observed July air temperature

Chapter 5

Holocene climate change and its effect on lake ecosystem production in Northern Victoria Island, Canadian Arctic

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Keywords: Chironomidae, Victoria Island Nunavut, Ecosystem production, Holocene, Paleoclimate reconstructions, Climate change

Abstract

A multi-proxy paleoenvironmental study from Lake WB02 (72.29°N, 109.87°W) on northern Victoria Island, Nunavut, Canada provides an 8.4 ka record of chironomid and ecosystem production. Mean July air temperatures over the Holocene for this region were inferred from the fossil record. The chironomid assemblages contained 33 taxa and were dominated by *Paracladius* and *Heterotrissocladius maeaeri*-type. Primary production and chironomid food availability inferred from sediment biogenic silica and loss-on-ignition at 550°C, and chironomid concentrations all exhibited synchronous patterns of change through time. Similar to other climatic records from across the Arctic, the sediment and fossil data from Lake WB02 support the hypothesis of a warm and productive early Holocene, a cool and generally unproductive mid to late Holocene and a return to a warmer, more productive environment in the past 100 years. Mean July air temperature reconstructions based on both the modern analogue technique (MAT) and weighted averaging partial least squares regression (WAPLS) failed to reflect these same changes. The difference between the qualitative and quantitative environmental reconstructions may be due to the restrictions associated with the use of these inference tools, the effect of which are more significant in unproductive ecosystems such as Arctic lakes.

Introduction

Many studies have documented how the current warming in the Canadian Arctic is impacting Arctic ecosystems (ACIA, 2005). Climatic changes affect lacustrine physical environments, which in turn directly influence ecosystem functioning (Kalff, 2001; Wetzel, 2001). The long-term consequences of these climate changes are less well understood, as there are few historical data of climate-ecosystem interactions, especially from the Arctic. Undisturbed lake sediments contain archives of past environmental conditions and can provide longer temporal records of climatic variability to which the measured recent warming can be compared. This is important as no direct quantitative information regarding climatic conditions is available before the last few centuries in the Arctic.

Paleolimnological studies provide a record of environmental change and identify important factors that affect ecosystems at long timescales. Most qualitative and quantitative reconstructions of past environmental variables in the Canadian Arctic are based on biological indicators such as pollen and diatoms (Gajewski, 1995; Douglas and Smol, 1999; Gajewski et al., 2000b; Gajewski and Frappier, 2001; Joynt III and Wolfe, 2001; Kerwin et al., 2004; Antoniades et al., 2005; Briner et al., 2006; Finkelstein and Gajewski, 2007a, Zabenskie and Gajewski, 2007; Podritske and Gajewski, 2007; Peros and Gajewski, 2008). As the number of available reconstructions increases, limitations associated with these reconstructions in Arctic regions are being identified. For example, in some cores from Arctic regions diatoms are missing, and the interpretation of this observation is not clear (Smith, 2002; Podritske and Gajewski, 2007). Pollen-based paleoclimate inferences may be underestimating past temperatures when based on pollen percentages alone (Peros and Gajewski, 2008).

Battarbee (2000) identified chironomids as a promising group of biological organisms to be used in paleotemperature reconstructions, and Walker and Cwynar (2006) recently provided an assessment of the factors that need to be considered when interpreting chironomid data in lake sediment cores. Biological proxies from higher trophic levels, such as chironomids are not only directly affected by climate but are also affected by the availability of food resources at the base of the food web and by the impact of top-down predation on their community. This highlights the need for studying multiple lines of evidence of climatic change within a single core, including fossil and sediment parameters such as organic, carbonate and biogenic silica content as these can act as checks on each other (Birks and Birks, 1980).

Only two chironomid-based environmental reconstructions spanning the Holocene exist for the Canadian Arctic Archipelago and both were carried out on Baffin Island (Briner et al., 2006; Francis et al., 2006). In this study, we provide the first multi-proxy analysis including chironomid fossil data from the Western Canadian Arctic, from a lake in Northern Victoria Island. The first objective was to document the postglacial chironomid community succession in this High-Arctic lake. The second objective was to quantitatively infer from the chironomid assemblages the changes in mean July air temperatures for the past 8.4ka. The reliability of the resulting reconstructions is evaluated. The third objective was to investigate changes in aquatic ecosystem production across different trophic levels in the context of climate change during the Holocene in the Arctic.

Methods

Lake WB02 (Figure 1), in the Wynniatt Bay region of northern Victoria Island (72.29°N, 109.87° W; 150 masl; area = 0.0231 km^2), was cored at its central point, where the depth to sediment is 7.4m. The pH of the lake was 8.0 and the conductance was 88 μS when the cores were collected. July and January air temperature normals recorded at Holman, the nearest weather station, were respectively 9.2°C and -28.6°C (1971-2000 normals; Meteorological Service of Canada, 2000). The vegetation in this region was categorized as prostrate shrub tundra (CAVM, 2003), and the bedrock was comprised of clastic and carbonate material of the Glenelg Formation (Frisch and Trettin, 1991). The region was deglaciated around 12 ka but a glacier readvance covered the area until 10 ka (Dyke, 2004).

Two replicate sediment cores were collected in June 1997 from the ice surface of Lake WB02 using a Livingstone piston corer of 5cm diameter and one meter length. A complete sediment sequence measuring 166cm was collected. The top 5cm of the core chosen for analysis was extruded in 0.5cm intervals in the field and the remaining sediment was wrapped in cellophane and aluminum foil, placed in plastic tubing and stored at 4°C. Water samples were collected approximately 1.5m below the ice surface at the time of coring for water chemical analysis.

Using a Bartington MS2C magnetic susceptibility meter, magnetic susceptibility was measured on the core at 1cm intervals and used to correlate the replicate cores. The core chronology was established by ^{210}Pb and ^{137}Cs dating (Department of Soil Sciences, University of Manitoba) and AMS radiocarbon dating (Beta Analytical Inc., Miami). Unsupported ^{210}Pb measurements reached background concentrations at 8 cm. A constant rate of supply (CRS) model was applied to the 16 ^{210}Pb determinations to derive the ages of the sediment (Oldfield and Appleby, 1984). The ^{137}Cs profile supports the ^{210}Pb profile. Seven radiocarbon dates were obtained by picking plant material, moss and chironomid remains from 2cm thick sections of the core. Between 8 and 86 cm, 15 samples were picked for dating but all lacked sufficient material. The conventional radiocarbon ages were converted into calibrated calendar years (cal yrs BP) by calculating the weighted average of the 2 sigma values generated by the CALIB program (Reimer et al., 2004). Dates are reported as ka (1000 yrs before present) with a base of AD 1997.

Both organic (LOI 550) and carbonate content (LOI 950) were estimated continuously throughout the core at 0.5cm resolution using a standard weight-loss on ignition technique at 550 and 950°C (Dean, 1974; Heiri et al., 2001). Organic and carbonate accumulation rates were also calculated. Accumulation rates account for differences in sediment densities between levels within a core (Itkonen et al., 1999; Meyers and Lallier-Vergès, 1999). Biogenic silica (BSi) was measured every 0.5 to 2 cm using a wet-alkaline digestion technique. This involved digesting the sediment with a weak base (1% Na_2C0_3) and subsampling the mixture after 2, 3, 4 and 5 hours (De Master, 1981; Conley, 1998; Conley and Schelske, 2001). Soluble silica in these aliquots was determined using a reduced molybdosilic acid spectrophotometric method (Parsons et al., 1984). Duplicate reference samples of known concentration provided by Conley's interlaboratory comparison of BSi measurements (1998) were included in each batch to ensure experimental replicability. All batches had reference BSi values within 1 standard deviation of the mean published BSi value (Conley, 1998). Biogenic accumulation rates were also calculated. Biogenic silica (BSi) in the sediment originates from siliceous organisms such as algae, sponge spicules and chrysophytes that lived in the water column and on the lake floor.

Chironomid extraction and mounting methods follow Walker (2001). Sampling intervals ranged from 0.5cm to 5cm with the top 5cm sampled at 0.5cm intervals. Sediment samples were first deflocculated in warm 10% KOH, then rinsed through a 90μm mesh with deionized water. The retained sediment was transferred to a Bogorov sorting tray. All head capsules in the samples were picked at 20-40x magnification and were slide mounted in

Entellan™. Where possible, a minimum of 50 whole chironomid head capsules were counted for each level (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001), therefore the volume of sediment processed for each depth ranged from $0.5cm^3$ to $7cm^3$. For levels not meeting the minimum head capsule criterion, only chironomid head capsule concentration data and not relative abundances were retained for statistical analysis. Primary reference material used for identifications included Oliver and Roussel (1983), Wiederholm (1983), Walker (1988; 2000), Heiri et al. (2004), Barley (2004), Larocque and Rolland (2006) and Brooks et al. (2007). Head capsules (HC) were identified to the species level where possible. Fossil chironomid concentrations were converted from volumetric (HC cc^{-1}) to dry weight concentrations (HC g^{-1}DW) to account for the difference in water content of each sample. To assess changes in community diversity through time, taxa richness and Shannon-Weiner's diversity index (*H'*) were calculated for all levels with more than 50 head capsules. Chironomid head capsule accumulation rate were also calculated.

A principal components analysis was used to summarize major trends in the chironomid taxa in relation to changes in sediment parameters. Only levels with over 50 HC and taxa with a mean relative abundance >1% averaged over all levels were included. Organic %, carbonate % and magnetic susceptibility were also included. A second analysis was performed on the same selection of chironomid percentages combined with a set of modern samples from northern Canada and Alaska (Barley et al., 2006) to provide a basis for interpreting the core assemblages.

Mean July air temperatures were estimated from the fossil data using both a transfer function (WAPLS 3 component with bootstrap cross-validation, $r^2_{boot}=0.818$, RMSEP=1.46°C; Barley et al., 2006) and the modern analogue technique (squared chord distance dissimilarity coefficient, weighted mean average, retaining 5 analogues). Only fossil levels containing greater than 50 head capsules were used in the reconstructions. Dissimilarity coefficients between the fossil assemblages and their closest modern analogues were examined to determine the geographic location of the best analogue. Confidence intervals (CI) of 75 and 95% were used to identify areas in the core where strong (< 75% CI), weak (75 to 95% CI) or no modern analogues (> 95% CI) existed for the fossil data (Overpeck et al., 1985; Barley et al., 2006).

Results

Core chronology and lithography

The 166cm core collected from Lake WB02 consisted mostly of clayey sediment with intermittent bands containing moss layers at 85.5 to 89cm, 98.5 to 125.5cm and 141 to 163cm. An age-depth curve was established from the 16 ^{210}Pb and 7 AMS dates by fitting a 4th order polynomial, forced through zero, to all of the dates (Table 1, Figure 2), but the chronology is poorly constrained from 8 to 80cm due to a lack of datable organic material. An age reversal was observed at 86 and 87.5cm, but remains within the error bars associated with each of these dates. The inferred basal date for this core was 8.4ka which is young based on the predicted deglaciation of the area. The sediment accumulation rate was greater before 5.5ka.

Overall, organic content was low, 2 to 17 %, while carbonate content ranged from 7 to 25%. Organic and carbonate profiles for both weight% and accumulation rates were broadly similar with larger values prior to 5.5ka and a more abrupt peak at the top (Figure 3). Conversely, magnetic susceptibility had maximum values between 5-2.5ka. From 5.5-1.0ka, organic and carbonate values were low, with little inter-sample variability. Magnetic susceptibility measurements were highest during this time, then systematically decreased from 2.8ka-0.03ka. From 1.0ka to present, organics first increased slowly and then more rapidly after 0.07ka, while magnetic susceptibility decreased.

Biogenic silica values were consistently very low, ranging from 0 to 2.5 BSi weight%. BSi weight % values and accumulation rates were marginally higher from 8.4-5.5ka, and then remained low until a rapid increase from 0.07ka to present time (Figure 3). With such low values, BSi dissolution, a common phenomena in Arctic systems, may have occurred throughout this core (Podritske and Gajewski, 2007; Paull and Gajewski, 2008).

Chironomid concentrations, diversity and community changes

The chironomid fauna of Lake WB02 was dominated by cold-tolerant, often cold stenothermic taxa and most were characteristic of oligotrophic lakes. Chironomid concentrations and accumulation rates were variable and higher between 8.4ka and 6.0ka, with maximum values at 7.5, 7.3, and 7.0ka, coinciding with peaks in organic matter (Figure 3). Head capsule concentrations reached maximum values of 488 HC g^{-1}DW, equivalent to 237 HC cc^{-1} of wet sediment. Chironomid concentrations and accumulation rates decreased at 6.0ka and remained low until around 0.05ka. Head capsule concentrations reached as low as 0.2HC cc^{-1} at three separate times during this period. Chironomid concentrations and accumulation rates increased again in the last 0.05ka.

A total of 33 taxa were recovered from the core. Overall taxa richness ranged from 9 to 21 taxa per level (Figure 3). Shannon-Weiner Diversity (*H'*) remained relatively low throughout the entire core, ranging from *H'*=0.73 to 1.02. Taxa diversity and richness were highest during the early Holocene. From 0.5ka to present there was a small increase in taxa richness and diversity.

The most abundant taxa throughout the core were the cold-tolerant taxa *Paracladius* and *Heterostrissocladius maeaeri*-type (Brooks et al., 2007). *Paracladius* was abundant throughout the past 8.4 ka (Figure 4). The warm-tolerant taxa of the subtribe Tanytarsina, notably *Micropsectra insignilobus*-type and *Paratanytarsus* spp. followed the same pattern as overall chironomid concentration (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007) (Figure 3). From 8.4-6.0ka, the most important taxa were *Paracladius* and taxa from the subtribe Tanytarsina (*Micropsectra insignilobus*-type, *Paratanytarsus* spp., *Tanytarsus* spp. and Tanytarsina spp.), and the subfamily Tanypodinae (*Procladius* and Tanypodinae spp.). *Corynocera ambigua*-type was only present between 7.9-7.6ka, comprising almost half of the assemblage. From 6.0-1.5ka there was a shift to a community dominated by *Heterotissocladius maeaeri*-type, *Stictochironomus* and *Paracladius* with a decreasing abundance of *Micropsectra insignilobus*-type, *Paratanytarsus* spp. and *Tanytarsus* spp.. From 1.5ka to 0.3ka *Paracladius* and *Heterotrissocladius maeaeri*-type decreased in importance while taxa from the Tanytarsina subtribe (*Micropsectra insignilobus*-type, *Paratanytarsus* spp., *Tanytarsus* spp.and Tanytarsina spp.) and *Abiskomyia* became more abundant. Between 0.3 to 0.07ka there was another shift in community composition characterised by the dominance of *Abiskomyia* taxa which comprised up to 47% of the assemblage. From 0.07ka to present, *Micropsectra insignilobus*-type, *Paratanytarsus* spp. and Tanytarsina spp. continued to increase while the abundance of *Abiskomyia* decreased. This decrease in *Abiskomyia* coincided with small increases in *Paracladius*, *Parakiefferiella nigra*-type, Tanypodinae spp. and other rarer taxa.

Data analysis

A principal components analysis (PCA) summarizes changes in the fossil assemblages in relation to the sediment parameters (Figure 5). The first two components explained 30 and 22% of the variance respectively. *Paratanytarsus* spp., *Tanytarsus* spp., and *Procladius* had high loadings on the first component (positive) as did *Zalutschia*-type B and *Abiskomyia* (negatively). Sediment carbonate content also had high loadings on this first component. There was an overall decrease in sample scores for this first component through time. Taxa with high loadings on the second component included *Heterotrissocladius maeaeri*-type, *Paracladius* and *Stictochironomus* (positively) and *Micropsectra insignilobus*-type *(*negatively). Organic and biogenic silica content had high negative loadings and magnetic susceptibility positive loadings on this component. The sample scores of this component increased from the bottom of the core until 1.0ka at which point they gradually decreased towards the top of the core, with a steeper decrease from 0.07ka to present. The PCA identified three groups of samples (scores), from 8.4-5.5ka, 5.5-0.5ka and 0.5.0ka to present.

Quantitative estimates of mean July air temperatures were constructed using both the Modern Analogue Technique (MAT) and Weighted Average Partial Least Squares (WAPLS) (Barley et al. 2006) (Figure 6). The reconstruction based on the MAT inferred cooler conditions from 8.4-5.0 ka, followed by an increase to 1.15ka, a decrease to 0.03ka and a warming in the uppermost samples. The reconstruction based on the WAPLS model showed no change in temperature from 8.4ka until 0.03 ka when a cooling occurred. This cool period was followed by a warming until present times. The MAT reconstructed larger between-sample temperature variations than the WAPLS. During the early Holocene, prior to 5.0ka, the MAT inferred cooler temperatures than the WAPLS (on average 3°C cooler) but both reconstructed similar temperatures after 5.0ka until the present.

The squared chord distances between fossil and modern analogues remain relatively high throughout the core, notably in the earlier Holocene with several samples were classified as having poor or weak modern analogues (Overpeck et al., 1985; Barley et al., 2006). A biplot of an analysis including chironomid percentages from both the WB02 core and the modern data illustrates that our fossil samples fall on the edge of the cloud made up by the training set lakes and ordinate only with a few Arctic and Northern Yukon sites present in the training set (Figure 7). This suggests that the modern samples are not entirely comparable to those in the core, as also shown by the MAT. Samples from the WB02 core had higher percentages of *Paracladius* and *Micropsectra* taxa than most modern samples from Boreal and Low Arctic Canada. Not surprisingly, samples that more closely resembled the fossil samples from WB02 were those from the Arctic Islands, however, there are only few available in the modern dataset.

Discussion

In Lake WB02, changes in chironomid concentrations, accumulation rates and organic and BSi weight percent and accumulation rates were all synchronous through time. Organic and BSi content are used here to infer past primary productivity (Meyers and Teranes, 2001; Cohen, 2003) and can provide a general idea of whole lake paleoproductivity (Cohen, 2003). Changes in organic and BSi content in modern lacustrian sediments across the Arctic have also been associated with changes in lake water nutrient concentrations (Fortin and Gajewski, 2009 [2]). Although the exact source of the sediment organic matter was not specifically examined in this study it has been documented that oligotrophic lakes receive large amounts of allochtohnous organic input (Wissmar et al., 1977; Cranwell, 1997; Hamilton et al., 2000; 2001) and that these external inputs of organic matter and nutrients to the water column can stimulate production within the lake (Wetzel, 2001). Changes in paleoproductivity as inferred by organic and BSi content have also been associated with changes in climate, specifically changes in temperatures (e.g. Qiu et al, 1993; Colman et al., 1995; Willemse and Törnqvist, 1999; Hu et al., 2003). Chironomids are arguably the most abundant zoobenthic organisms in profundal sediment, in sheer number, in number of species and in overall biomass (Hillsenhoff, 1991). Chironomid abundance, which we interpret as chironomid production, has been used as indicators of paleo-benthic production in lake sediment (Itkonen et al., 1999).

The coherence between changes in chironomid, organic and to a lesser extent BSi accumulation and concentration in this lake is an indication that past environmental changes are simultaneously affecting different trophic levels of the aquatic food-web (Quinlan et al., 2005). Chironomid larvae are detritivors, filter feeders and grazers who feed off of algae, small plants, organic detritus and other invertebrates (Oliver, 1971). The abundance of chironomids and their community composition are directly affected by changes in climate but also indirectly affected by changes in availability of primary producers and other organic material. In fact, food availability and quality can affect larval growth rate, fecundity and survivorship (Ward and Cummins, 1979; Pinder, 1986), chironomid community composition and chironomid concentration (Pinder, 1986). Potential indicators of chironomid food resources are sediment organic matter as it is mostly derived from primary producers such as algae and plant material (Kalff, 2001) and biogenic silica (BSi) as it measures diatom abundance and production in sediments (Pinder, 1986; Conley, 1988; Ragueneau et al., 1996; Itkonen et al., 1999; Wetzel, 2001). Therefore, in Lake WB02, the coherence in changes in both primary production and chironomid concentration is suggestive of changes in past environmental conditions, and in the case of this chironomid community, may also reflect the indirect impact of changes in chironomid food availability at the base of the food chain.

The sedimentary history of Lake WB02 can be broadly divided into two phases. The first phase, lasting until 5.5ka is characterised by generally high organic and chironomid and to a lesser extent BSi concentrations. Sediment accumulation rates were also high during this phase. A major change occurred at 5.5ka, when sediment accumulation rates declined, as did concentrations of chironomids, organic and BSi. When concentrations are normalized to annual rates (ie accumulation rates) to account for this change in sedimentation rate at 5.5ka, the conclusion remains the same; prior to 5.5ka, the lake was more productive than subsequently. Because of the weakness of the chronology, we cannot interpret short-term variability in the various components of ecosystem production. Thus, we propose that a large change in the climate occurred at this time that caused a reduction in freshwater production.

Along with the change in production in the mid-Holocene, in Lake WB02, there were three important transitions in chironomid community assemblages, at 5.5ka and 1.0ka and 0.07ka. The biodiversity shifts at 5.5ka and 0.07ka, and to a lesser extent at 1.0ka were accompanied by changes in chironomid concentration and accumulation rates, with highest values in the early Holocene.

The early to mid Holocene (8.3ka to 5.5ka) was characterised by maximum values and high variability of chironomid accumulation rates, concentrations and primary production, suggesting warmer conditions during this time. Both cold-tolerant *Paracladius* and warm-water taxa from the subtribe Tanytarsina, specifically *Micropsectra insignilobus*-type, (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007) dominated the assemblages. Briner et al. (2006) also observed a dominance of the Tanytarsina subtribe in the early Holocene in Lake CF3 on Baffin Island. However, the warm period at WB02 coincides with the base of the sequence, so it is not clear if this dominance is a consequence of their preference for warmer conditions or to their potential role as colonizers. *Procladius* and *Chironomus anthracinus*-type, indicators of productive ecosystems were also present (Brooks et al., 2007). *Corynocera ambigua*-type was dominant for a short period of time, as was also documented by Brooks et al. (2007). It is possible that a combination of favourable climatic conditions and greater availability of food may have contributed to high chironomid taxa richness and diversity. In addition, the abundance and accumulation rates of both cold and warm tolerant taxa increased. If taxa with different temperature optima are responding similarly to increasing temperatures then it can be hypothesised that individual chironomid production may in fact all respond in the "same direction" as a function of increasing temperature and more favourable conditions, regardless of their individual temperature optima.

The mid to late Holocene (5.5ka to 1.5 ka) may have been cooler and less variable than the early Holocene, leading to low primary production and chironomid accumulation rates and concentrations as well as lower taxa richness and diversity. A possible decline in available food resources, as seen in the decrease in organic content, coupled with less than favourable conditions for chironomid development could partially explain the decrease in chironomid taxa richness and diversity as well as the decrease in overall chironomid and individual taxa concentration and accumulation rate. During this time, the species assemblages were dominated largely by cold-tolerant taxa such as *Paracladius*, *Heterotrissocladius maeaeri*-type and *Stictochironomus* and warm-tolerant taxa were effectively absent.

During the last 1.5ka, the climate in northern Victoria Island alternated between several warmer and colder periods. From 1.5 to 0.8ka was a warming period, as indicated by an increase in organic production and resource availability and to a lesser extent, chironomid accumulation rate of warmer taxa. A number of taxa found in the chironomid assemblages during the warmer early Holocene once again increased in abundance in these sediments, such as taxa from the Tanytarsina subtribe. The timing of this warming coincides roughly with the Medieval Warm Period in this part of the central Canadian Arctic (LeBlanc et al., 2004). Temperatures then cooled from 0.3-0.07ka, as inferred by the dominance of *Abiskomyia*, a taxon that occurs in cold, oligotrophic lakes (Cranston et al., 1983). At its maximum, it represented nearly half of the chironomid population. An increase in abundance of *Abiskomyia* was also noted in the more recent sediments of both Fog Lake and Brother of Fog Lake in the Cumberland Peninsula of Baffin Island (Francis et al., 2006). The timing of its appearance in the study coincides with the Little Ice Age (Overpeck et al., 1997). From 0.07ka to the present, there was a rapid warming in the study area. This was made evident by a rapid increase in primary production and chironomid accumulation, as well as an increase in the relative abundance of warm-tolerant taxa of the Tanytarsina subtribe. Taxa richness and diversity both increased during this time. Although this increase in overall primary production and chironomid accumulation was quite rapid and of great amplitude, it remains comparable to fluctuations in organic and chironomid accumulation that occurred during the early Holocene.

Independent paleoclimate records provided by the GISP2 oxygen isotope data (Alley 2000), Agassiz ice core melt percentages (Fisher et al., 1995) and the Lake KR02 pollen curve (Peros and Gajewski, 2008) also indicate warmer temperatures before 6.0ka. Kaufman et al. (2004) inferred maximum Holocene temperatures between 8.6ka and 4.9ka in this region. A neoglacial cooling inferred for Lake WB02 during the mid to late Holocene corresponds with the decrease in ice melt in the Agassiz ice core (Fisher et al., 1995) and decrease in pollen concentrations in Western Victoria Island (KR02; Peros and Gajewski, 2008), Northern Boothia (JR01; Zabenskie and Gajewski, 2007) and Somerset Island (RS29 and RS36; Gajewski, 1995). Diatom production decreased during this period in Western Victoria Island (KR02; Podritske and Gajewski, 2007), Prince of Wales (PW03; Finkelstein and Gajewski, 2007b), Boothia (JR01; LeBlanc et al., 2004) and at Baffin Island (CF3; Briner et al., 2006). The chironomid-inferred July air temperatures from Lake CF3 on Baffin Island indicate that the cooling occurred slightly earlier on Baffin Island than at WB02. A rapid warming from 0.07ka to the present, inferred from an increase in primary and secondary production and from the shift in chironomid community composition at Lake WB02, is also documented at sites across the Arctic (Overpeck et al., 1997). Changes observed in primary production and chironomid accumulation and in food availability at the base of the food-web at Lake WB02 over the Holocene are synchronous, within the errors of the chronologies, to changes observed in chironomid, pollen and diatom-based climate studies across the Arctic and correspond to fluctuations in temperatures inferred from independent Arctic climatic records.

Mean July air temperatures inferred using the MAT and WAPLS presented different long-term trends. Indeed, the changes estimated by the two numerical methods indicate little change in the Holocene (WAPLS) or a slight warming in the mid Holocene (MAT). The timing and direction of these inferred air temperatures changes does not concord with the qualitative interpretation of sediment and fossil data in the core. Other studies have revealed differences between MAT and transfer function reconstructions, resulting at least in part from limited modern analogues in the training sets (Birks, 1998; Lotter et al., 1999; Peros and Gajewski, 2008).

There are several potential reasons for the discordance in the numerical paleotemperature estimates and the concentration, qualitative interpretation based on assemblages and other proxy-climate records. One possible explanation for the differences involves the density of sites and size of the training set used to infer the mean July air temperatures from the fossil data. Almost half of the fossil assemblages had weak or no modern analogues, providing less reliable reconstructions (ter Braak, 1995; Birks, 1998). Although not severely non-analogue, the ordination shows that the fossil assemblages, which all closely ordinate, are only located on the edge of the cloud of points represented by the modern samples. This suggests that for some reason, the chironomid assemblages living in the past were in some critical ways different from the modern assemblages. For example fossil assemblages contain a large quantity of *Paracladius*, which is not present in the modern lakes, but the ecological reasons for this are not clear. Although this training set does cover a very large range of environmental conditions, it does not contain a sufficient density of sites within the various regions, especially in the Arctic. This is indicated by the large differences in mean July air temperatures between the two closest analogues for certain fossil levels considered as having the strongest modern analogues (Table 2). As an example, three out of the four pairings of modern and fossil assemblages with the smallest dissimilarity had differences between the temperatures of their respective two best analogues up to 68% of the total temperature variability inferred for the last 8.4ka. There is, therefore, a need to expand the modern training sets to include a greater range of environmental variability and also to increase the density of sites within the range.

Another possible explanation for the difference between the qualitatively inferred and quantitatively reconstructed temperatures may be the biases inherent to the experimental design and the statistical tools used to create the modern training sets and the reconstructions.

Arctic aquatic ecosystems are generally low productive systems which can result in lower head capsule (HC) concentrations. The training set that was used for these reconstructions included only modern sites for which over 75 HC could be counted, and although choosing a higher minimum number of HC improves the chances of encountering more taxa in more productive lakes (Quinlan and Smol, 2001), this tends to eliminate less productive systems from the training set that are likely to be analogues for some of the fossil data found within Arctic cores. It is common in Arctic cores to have levels with less than 50 HC that are not used in reconstructions, which typically require a minimum of 50 HC (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001). Favouring higher count sums in training sets, compounded with the inability to include levels with lower count sums in the reconstructions, creates biases towards predicting warmer temperatures and more productive systems. It is essential to develop more extensive modern chironomid databases and consider relaxing strict minimal count criteria to allow more flexible development of transfer functions and application of the MAT. However, it is possible that even if this were done, the high productivity of early Holocene ecosystems in the Arctic would remain non analogue, complicating attempts to quantify past conditions.

Finally, it is possible that in the Arctic context, past climatic changes are more greatly manifested in the changes in chironomid concentrations through time rather than in the changes in chironomid community composition (Itkonen, 1999). To reconstruct past environmental conditions, inference tools such as the MAT and the WAPLS focus solely on changes in relative abundance of the chironomid taxa. However changes in overall chironomid production also contain valuable information regarding past environments. In systems of low productivity, such as the Arctic lakes, it is necessary to combine both types of data – production and species relative abundance – to interpret past environment conditions.

Conclusion

Fossil chironomid assemblages were analysed in a lacustrine sediment core taken from Lake WB02 in the High Arctic of Victoria Island, NWT. Dominant taxa in the core included *Paracladius*, *Heterotrissocladius maeaeri*-type and taxa from the subtribe Tanytarsina. Inferred mean July temperature over the Holocene using both the modern analogue technique (MAT) and weighted averaging partial least squares regression (WAPLS) showed some significant differences and further did not concur with the interpretation of the core sediment parameters or fossil data. It is concluded that the quantitative methods tend (a) to favour environmental reconstructions from the more productive assemblages and (b) do not account for the significant impact that climatic variability may have on overall chironomid accumulation.

Sediment and fossil proxies from this core indicated a variable but warmer and more productive early Holocene, a more stable, cooler and less productive mid Holocene and a return to warmer conditions in recent times. Shifts in chironomid and primary production and changes in chironomid community composition within this lake were synchronous to changes in other proxy climate records from various regions across the Arctic, indicating the impact of large-scale climate variations on the functioning of Arctic aquatic ecosystems. However, it remains unclear if the effect of climate on chironomid communities is direct, through differential physiological response of taxa to changes in temperature or indirect by the effect of the climate variations on the abundance and composition of the chironomid food source.

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Table 1 Radiocarbon dates and calibrated calendar ages (ka) (Reimer et al., 2004) for Lake WB02

Lab code (Beta-)	Depth (cm)	Mean depth (cm)	Conventional radiocarbon age yr BP	cal yr BP 2σ lower	cal yr BP 2σ upper	Relative area under calibrated age curve	cal yr BP	Age ka ± 2σ (before 1997)	Material dated
215188	85.0-87.0	86.0	5320 ± 40	5955	5955	0.001	6104	6.151 ± 0.155	plant parts, chironomids
				5991	6211	0.978			
				6247	6265	0.021			
210913	86.5-88.5	87.5	5240 ± 40	5917	6031	0.676	6017	6.064 ± 0.130	plant parts
				6039	6073	0.070			
				6075	6120	0.157			
				6148	6177	0.096			
215189	99.0-101.0	100.0	5420 ± 40	6029	6039	0.009	6232	6.279 ± 0.136	plant parts , chironomids
				6119	6149	0.048			
				6177	6300	0.944			
215186	123.0-125.0	124.0	6230 ± 40	7010	7129	0.448	7141	7.182 ± 0.123	plant parts, chironomids
				7144	7255	0.552			
210914	127.5-129.5	128.5	6380 ± 40	7252	7420	1.000	7336	7.383 ± 0.084	plant parts , chironomids
215187	151.0-153.0	152.0	7160 ± 40	7875	7892	0.026	7982	8.029 ± 0.083	plant parts, chironomids
				7929	8040	0.974			
215190	165.0-167.0	166.0	7400 ± 40	8067	8082	0.015	8249	8.294 ± 0.138	plant parts, chironomids
				8162	8342	0.985			

Table 2 Diagnostic analysis of the two best analogues for fossil levels having strongest modern analogues

Depth (cm)	Age (ka)	Mean July temperature (°C) inferred by the MAT	First closest analogue		Second closest analogue	
			SCD	temperature (°C)	SCD	temperature (°C)
3.75	0.048	5.84	7.73	4.0	8.37	7.1
0.75	0.005	6.17	8.54	7.1	9.66	4.0
49	3.112	10.52	8.70	10.9	16.08	10.1
4.25	0.058	5.52	8.93	7.1	9.29	4.0

MAT is modern analogue technique retaining the 5 closest analogues; SCD is squared chord distance dissimilarity coefficient

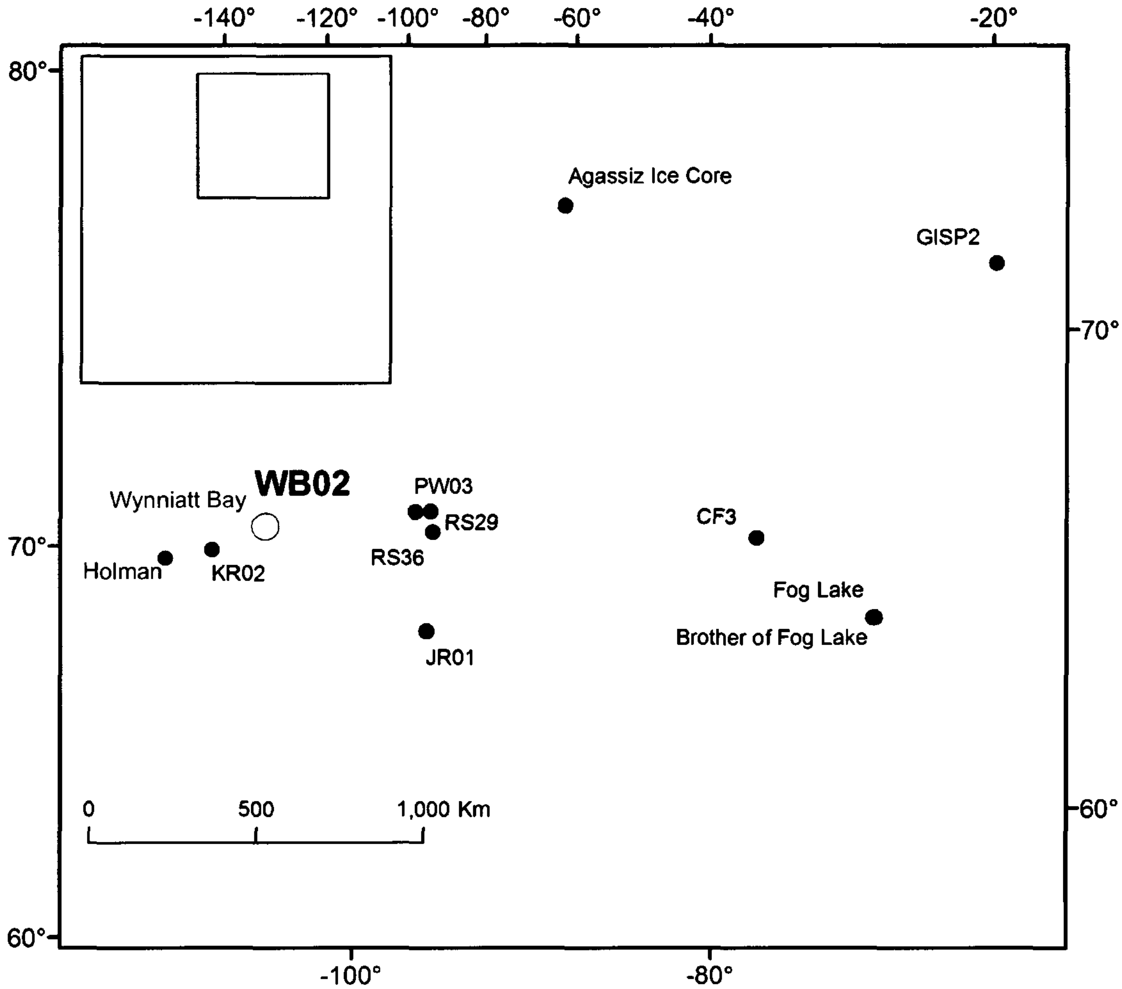

Figure 1 Location of Lake WB02 in the Canadian Arctic. Also included are the locations of the other sites mentioned within the text

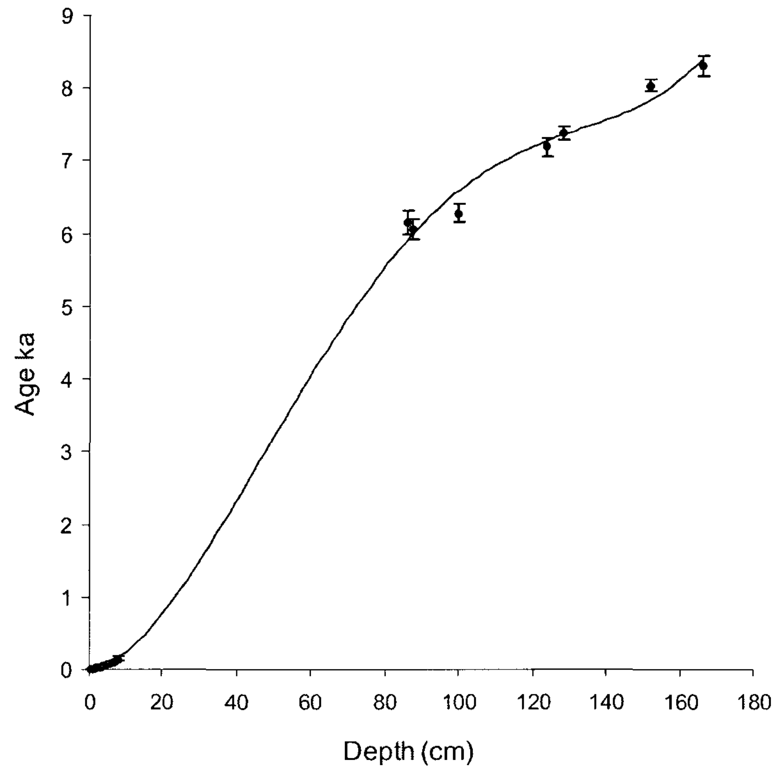

Figure 2 Age depth curve for Lake WB02 based on ^{14}C and ^{210}Pb dating. All ages in ka with base AD1997

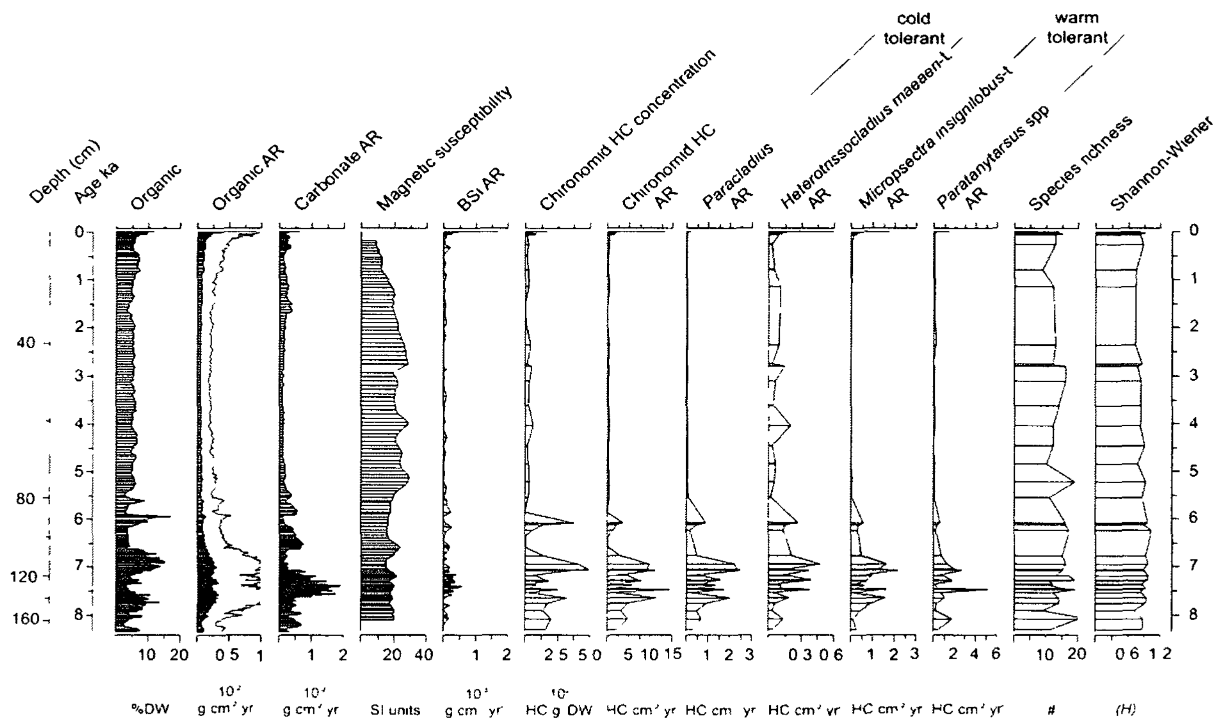

Figure 3 Sediment analysis of Lake WB02 including both organic weight % and accumulation rates (AR) (LOI 550) carbonate AR (LOI 950), magnetic susceptibility and biogenic silica AR (BSi). A 4x exaggeration line is included on the organic AR plot. Summary plot of chironomid head capsule (HC) concentration and AR, and AR of *Paracladius* and *Heterotrissocladius maeaeri*-type taxa and warm-tolerant *Micropsectra insignilobus*-type and *Paratanytarsus* spp. head capsules as well as taxa richness and Shannon-Wiener (*H'*) diversity index from Lake WB02

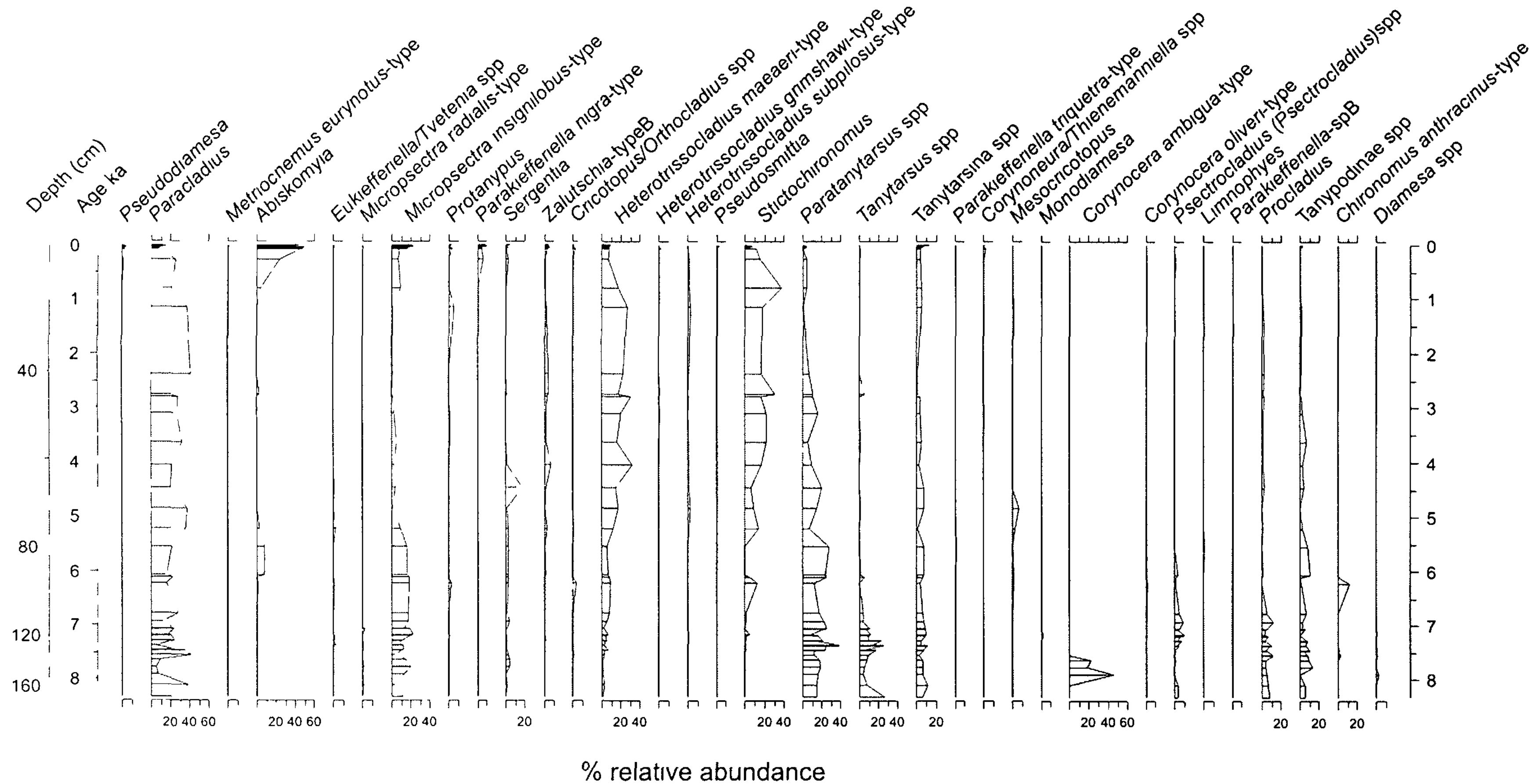

Figure 4 Relative abundance (%) of chironomids from Lake WB02. Taxa are ordered from cold (left) to warm (right) according to optima, ranking modified from Barley et al. (2006). Each tick mark on the x axis represents 10% increment of relative abundance

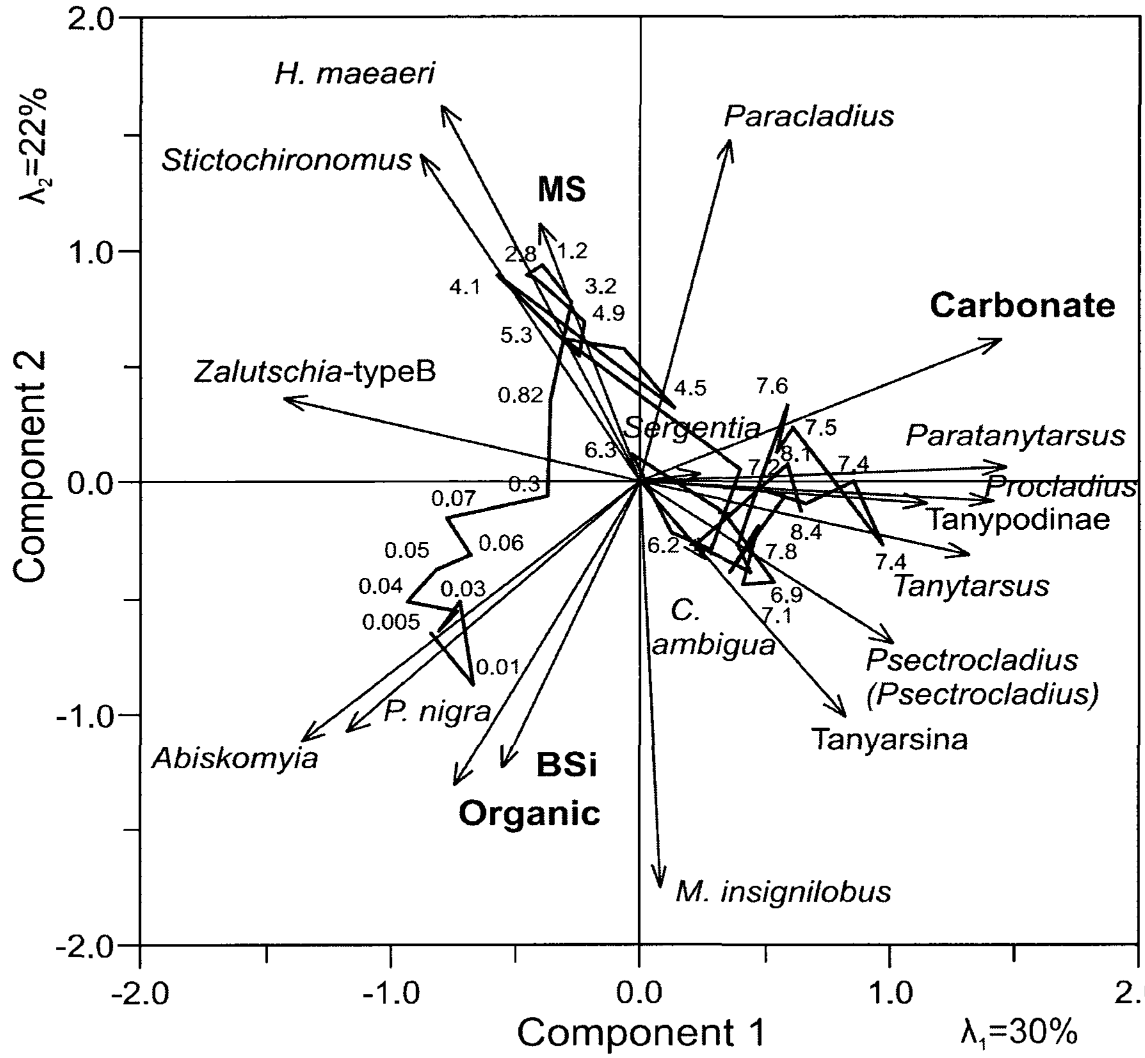

Figure 5 Principal components ordination of taxa and sediment parameters from core WB02. *C. ambigua=Corynocera ambigua*-type, *H. maeaeri=Heterotrissocladius maeaeri*-type, *M. insignilobus=Micropsectra insignilobus*-type, *P. nigra=Parakiefferiella nigra*-type and MS=magnetic susceptibility, BSi=biogenic silica (weight%). *Paratanytarsus*, Tanypodinae, *Tanytarsus* and Tanytarsina are all spp.. Organic and carbonate data are weight%. Dates (ka) for a selection of samples are included on the graph. The line connects the samples chronologically

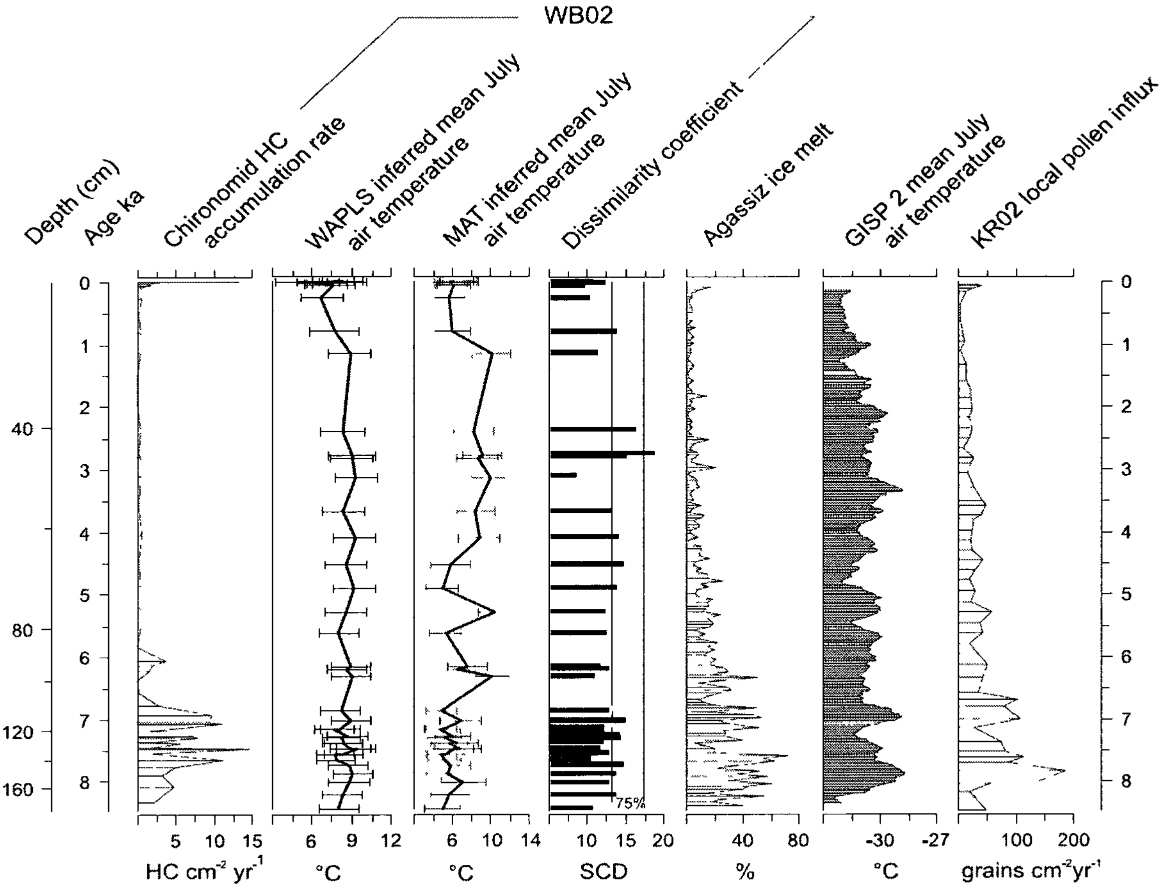

Figure 6 Paleoclimate reconstruction based on chironomids of Lake WB02 compared to several independent climate records: Agassiz ice melt % (Fisher et al., 1995), central Greenland mean July air temperatures (Alley, 2000) and KR02 local pollen influx (Peros and Gajewski, 2008) which were truncated at 8.5ka. SCD= square chord distance

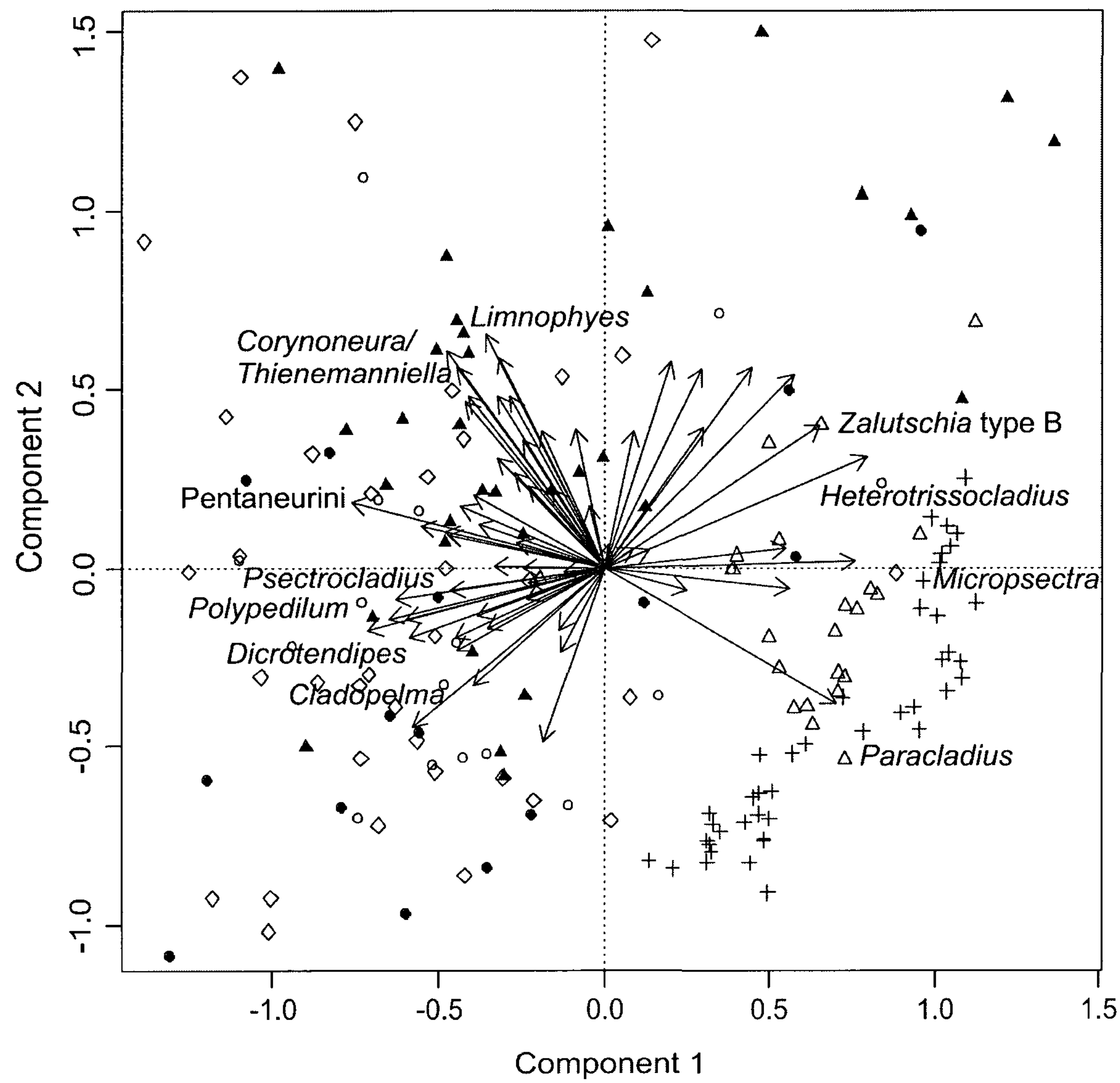

Figure 7 Principal components ordination including fossil chironomid percentages from core WB02 and of taxa found in a geographic array of modern samples (Barley et al., 2006). Symbols are as follow: ● modern Alaska sites, ○ modern Yukon sites, ▲ modern Mackenzie Delta sites, Δ modern Arctic sites, ◊ modern British Columbia sites, + fossil WB02 samples. Only taxa with loadings ≥ 0.6 on both the first and second component are labeled on the biplot

Chapter 6

Postglacial environmental history of western Victoria Island, Canadian Arctic

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Keywords: Chironomids, Holocene, Canadian Arctic, Victoria Island, Climate Change, Quantitative Paleoclimate Reconstruction, Modern Analogue Technique, WAPLS, diatoms, pollen

Abstract

Changes in chironomid species assemblages and community dynamics at Lake KR02, western Victoria Island were analysed to produce a record of environmental change over the Holocene for the western Arctic. Past air temperatures were inferred from the chironomid record using transfer function and modern analogue techniques, and past lake water pH was reconstructed using sediment carbonate and biogenic silica content. The early Holocene (10.2-6.5 ka) was a warm period of high aquatic and terrestrial production. A further change in environmental conditions occurred at 4 ka and lasted for the next two millennia. Conditions warmed abruptly at 1.6 ka, and rapidly cooled at ~1.0 ka. A warming then started at 0.14 ka and continued through to recent times, although temperatures still remained cooler than those experienced prior to 6.5 ka. The climatic changes over the Holocene as recorded at Lake KR02 are consistent with those inferred from independent records from other sites on Victoria Island and across the Arctic.

Introduction

Instrumental records document a warming during the past century at a number of sites across the Arctic (ACIA, 2005). Interpretations of paleolimnological data, extracted from Arctic lake sediment cores, also show changes in species composition and production, and these have been interpreted as a result of this recent increase in temperature (e.g., LeBlanc et al., 2004; Smol et al., 2005; Podritske and Gajewski, 2007). Paleoenvironmental proxy records extend back before the instrumental record and indicate that the climate has been continually changing over the last 10,000 years in the Canadian North, as elsewhere (e.g., Gajewski and Atkinson, 2003). Questions remain, however, about the timing and magnitude of Holocene climate variability in the Arctic.

Lake sediments archive past environmental conditions through the preservation, within the sediment matrix, of fossils of organisms and material that were present in the lake or on the surrounding landscape. From these proxy climate records, past environmental conditions can be inferred. These archives are a major source of information about past climates, although there are few such records from the Canadian Arctic that span the entire postglacial period (Gajewski and Atkinson, 2003). However, interpretation of these records is not necessarily straightforward, and a consistent and quantitative interpretation of the postglacial climates of the Canadian Arctic region is still lacking.

This study will examine the chironomid fossil record for Lake KR02 located on western Victoria Island. A high-resolution diatom study was previously conducted on this core (Podritske and Gajewski, 2007) and Peros and Gajewski (2008) provided a detailed pollen record. There exist, however, certain discrepancies between the interpretations of these records. In particular, periods of low diatom production, typically interpreted as indicating cold temperatures, were identified when the pollen record suggested warm conditions. Although changes in pollen influx showed large changes from the early to late Holocene, estimates of past temperature showed less variability.

The purpose of this study was to determine, based on the chironomid record, what climatic conditions existed in the western Victoria Island region over the Holocene. We compare the chironomid record to the pollen and diatom records, allowing us to better understand the behaviour of these two groups of organisms and pollen through time and account for the timing and extent of both changes in overall production of the lake ecosystem and in the biodiversity of the species assemblages. Finally, the climatic record for western Victoria Island will be compared to other Holocene records from the central Canadian Arctic. By comparing the various proxy climate records from western Victoria Island among themselves, as well as to other records from the region and then to sites from across the Arctic we will be better able to determine the geographical extent and timing of the climatic changes occurring throughout the Holocene.

Study area

Lake KR02 is located in the Kuujjua River region of northwestern Victoria Island in the Northwest Territories of the Canadian Arctic (71.34°N, 113.78°W, 299MASL; Figure 1). The lake has a surface area of 7,900 m^2 and a maximum depth of 6.2 m at the coring location. Lake KR02 is oligotrophic (TP=0.226μmol L^{-1}) and circumneutral (pH= 7.3).

The lake is underlain by clastic and carbonate sediments as well as basalts from the Kilian Group of the Shaler Formations and the Natkusiak Formation (Frisch and Trettin, 1991). It is surrounded by prostrate shrub tundra (CAVM team, 2003). January and July air temperature normals (1971-2000) for the closest weather station (Ulukhaktok/Holman) are -28.6°C and 9.2°C respectively (Meteorological Survey of Canada, 2006). Further information regarding the environmental characteristics of Lake KR02 can be found in Bouchard et al. (2004), Podritske and Gajewski (2007) and Peros and Gajewski (2008).

Field methods

A sediment core measuring 411 cm was taken from the central location of Lake KR02 using a 5-cm diameter Livingston piston corer. The top 20 cm of the core was extruded at 0.5 cm intervals in the field to preserve the sediment-water interface. The remaining sediment was wrapped in layers of plastic wrap and foil and stored at 4°C. Lake water was collected from 1.5 m below the ice for water chemical analysis. Complete water chemistry results for Lake KR02 are available in Bouchard et al. (2004).

Laboratory analysis

The core chronology was established using 9 AMS radiocarbon dates and ^{210}Pb dating, which provided an age estimation for each of the top 21 cm (Table 1 and Table 2). The resulting age-depth model, based on a linear interpolation after calibration is described in Peros and Gajewski (2008) (Figure 2). Calibrated ages are reported in this manuscript as ka (1000 years before present), with a base of AD 2000. The basal date of ~10.5 ka of the sediment core is extrapolated from the age-depth model as the oldest radiocarbon date obtained was ~9.8 ka old. Dyke (2004) proposes that the Kuujjua Region was likely deglaciated by ~12 ka.

Sediment analyses, including sediment organic, carbonate and biogenic silica content estimations and magnetic susceptibility (MS) measurements followed standard protocols and are outlined in Podritske and Gajewski (2007). Sediment organic, carbonate and biogenic silica content that were previously reported as dry weight % were also converted to dry weight accumulation rates (g cm^{-2} yr^{-1}).

Chironomid head capsules and mandibles were extracted and identified for a total of 116 levels following methods in Walker (2001). Sediment for chironomid analysis was sampled every 0.5 cm for the top 20 cm of the core and at 1 to 5 cm intervals for the remaining portion of the core. Samples of between 2 and 7 cm^3 of wet sediment, taken over 0.5cm wide thicknesses of sediment for the top 20 cm and 1 cm wide thicknesses for the rest of the core, were soaked in warm 10% KOH. The deflocculated material was sieved through 90μm-mesh using deionised water. Midge head capsules and mandibles were then picked from a Bogorov sorting tray using 20-40x magnification, and mounted on slides using Entellan™. To account for differences in sedimentation rate chironomid accumulation rates (HC $cm^{-2}yr^{-1}$) are also presented.

Chironomid identifications were made using taxonomic keys provided by Walker (1988; 2000), Barley et al. (2004), Heiri et al. (2004), Larocque and Rolland (2006) and Brooks et al. (2007). *Tanytarsus* spp., *Micropsectra* spp. and *Paratanytarsus* spp. were identified using Heiri et al.'s (2004) identification key. *Heterotrissocladius* spp. identifications followed Larocque and Rolland (2006) and *Zalutschia* spB is according to Barley et al. (2006). Oliver and Roussel (1983) and Wiederholm (1983) reference manuals were also consulted. Where possible, head capsules were identified to the species group or morphotype and these specific identifications were subsequently selectively combined to facilitate analysis. *Micropsectra* spp. includes both *Micropsectra radialis*-type and *Micropsectra insignilobus*-type, although *Micropsectra radialis*-type is only present in 4 levels and only accounts for less than 1% of all the specimens in the *Micropsectra* spp. group. Similarly, *Paratanytarsus* spp. includes *Paratanytarsus austriacus*-type, *Paratanytarsus penicillatus*-type and indeterminate *Paratanytarsus austriacus / penicillatus* – type. *Tanytarsus* spp. includes *Tanytarsus lugens*-type, *Tanytarsus mendax*-type and indeterminate *Tanytarsus lugens/mendax* spp. All morphotypes and intermediary forms of *Cricotopus* and *Orthocladius*- type species have been combined into *Cricotopus/Orthocladius* spp.. *Cricotopus cylindraceus*-type, *Cricotopus (Isocladius) intersectus*-type, *Cricotopus (Isocladius) laricomalis*-type and *Cricotopus (Isocladius) sylvestris*-type, as identified after Brooks et al. (2007), were found at various levels throughout the core. As the proportion of indeterminate *Cricotopus / Orthocladius* remained greater than the identifiable ones, all *Cricotopus / Orthocladius* morphotype were combined into *Cricotopus / Orthocladius*-spp. *Heterotrissocladius maeaeri*-type includes four morphotypes of this species. *Heterotrissocladius maeaeri*-type1-dark has no accessory tooth on the median tooth and the head capsule is dark from the bottom of the mentum to the post occipital plate. *Heterotrissocladius maeaeri*-type1-light also has no accessory tooth on the median tooth but is only slightly pigmented just below the mentum. *Heterotrissocladius maeaeri*-type2-dark and *Heterotrissocladius maeaeri*-type2-light are similar to type-1 forms but type-2 specimens have an accessory tooth on either side of the median tooth. The less pigmented head capsules may be younger instars of the darker ones.

Information regarding chironomid temperature optima and particular taxon environmental preferences was taken primarily from Barley et al. (2004), Gajewski et al. (2005), Francis et al. (2006), Larocque et al (2006) and Porinchu et al. (2009a). Further qualitative information regarding ecological preferences was taken from Brooks et al. (2007).

In the following, all characteristics relating to a taxon's optimal temperatures and ecological preferences are relative to the other taxa found in the core. However, based on the available North American chironomid training sets there are conflicting results with respect to the optimal air temperatures of some of the important taxa in core KR02. This is due in part to the particular geographic sample set used by various authors to define temperature optima and tolerance, but also to differences in taxonomic resolution in the existing modern Arctic chironomid data (Gajewski et al., 2005; Barley et al., 2006; Francis et al., 2006; Larocque et al., 2006; Porinchu et al., 2009a). When considering taxa from the subtribe Tanytarsina, it is difficult to resolve the temperature optima of the different taxa within this subtribe. For example, *Micropsectra* spp. is identified as a cold-tolerant genus by Barley et al. (2006) and Brooks et al., (2007), but is considered tolerant of intermediate temperatures in Porinchu et al. (2009a). Furthermore, Larocque et al. (2006) separate *Micropsectra* head capsules to morphotype and identify *Micropsectra insignilobus*-type as also being tolerant of intermediate condition and *M. radialis*-type as preferring colder conditions. Brooks et al. (2007) also identify *Micropsectra insignilobus*-type as preferring warmer conditions than *M. radialis*-type. *Cricotopus/Orthocladius* is another complex group whose optimal temperatures can range from cold tolerant in Porinchu et al. (2009a), to moderate in Francis et al. (2006), to moderate-warm in Barley et al. (2006). A similar problem occurs with *Corynocera oliveri,* which is described as a warm-tolerant taxon by Barley et al. (2006), but appears to indicate more moderate to cold conditions (Porinchu et al., 2009a; Larocque et al., 2009). Gajewski et al. (2005) had previously determined that the distribution of *C. oliveri* in the Arctic had no significant relation to temperature and it was generally found in lakes with higher dissolved organic carbon (DOC) concentrations. *Sergentia,* which is identified as preferring cold conditions in the Porinchu et al. (2009a), Larocque et al. (2006) and Francis et al. (2006) training sets, indicates cold to moderate air temperatures according to Barley et al. (2006). We have taken into account these differences in our interpretation.

Data analysis

A principal component analysis (PCA) was performed using only the chironomid fossil data (relative abundances %). Only levels with more than 30 head capsules and taxa with a mean relative abundance >1% averaged over all levels were included. Using a lower minimum total head capsule for inclusion than the often-used 50 HC (Heiri and Lotter, 2001; Quinlan and Smol, 2001; Larocque, 2001) is necessary in very unproductive Arctic ecosystems in order to retain any information regarding the most unproductive periods in the history of these Arctic lakes (Fortin and Gajewski, 2010a [5]). A total of 9 levels out of the 92 retained had head capsule counts between 30 and 40.

Using data from Barley et al. (2006), mean July air temperatures were reconstructed from the KR02 midge fossil data removing rare taxa from both the training set and the downcore data. Chironomid taxonomy from the KR02 core was harmonized with that of Barley et al. (2006) prior to performing the reconstruction. All *Tanytarsus* and *Paratanytarsus* taxa from the KR02 core, as well as all remaining taxa from the subtribe Tanytarsina that could not be further identified were combined as Tanytarsina-other. All *Heterotrissocladius* taxa were also combined as *Heterotrissocladius* spp.. Environmental reconstruction using both a weighted average partial least squares transfer function (WAPLS with three components and a bootstrap cross-validated) and a modern analogue technique (MAT, squared chord distance dissimilarity coefficient, retaining 5 analogues) were performed. The WAPLS model provided the most robust reconstructions (best performance statistics; Barley et al., 2006), and the MAT was also used in order to show the geographical location of the closest modern analogues to the downcore fossil data and assess the appropriateness of the modern data as analogues of the fossil assemblages. All taxa found in the core were present in the training set. Only levels with 30 head capsules or more were included in the reconstruction.

Based on sediment carbonate and BSi weight % from the sediment core, a pH reconstruction was constructed using a model derived by Fortin and Gajewski (2009 [2]) (r^2=0.51, p=1*10^{-4}).

Results

Organic weight % and accumulation rate (AR) profiles both showed a long term increase of organic matter through time (Figure 3). Sediment BSi weight % and AR were highest between 10.2-9.5 ka and 7.2-6.5 ka with two increases starting at 4.0 ka and again around 0.2 ka until the recent sediment. BSi content is an index of diatom and chrysophyte production. These periods of high BSi weight % and AR correspond to slightly elevated values of organic accumulation rates. These peaks occurred every ~3000 years (Figure 3). The abrupt nature of the changes of the organic AR at various points in the Holocene is due to the linear interpolation used to create the age-depth curve; using a different age-depth model would smooth the abrupt transitions in organic AR, however the overall pattern would remain the same. Carbonate percentages are high between 6-4.5 ka and magnetic susceptibility was high at the bottom of the core, decreased at around 10 ka and remained low to the present (Figure 3).

Chironomids

Concentration and accumulation rate

Chironomid head capsule (HC) concentrations ranged from 1 to 116 HC cm^{-3} (Figure 3). Both chironomid concentrations and chironomid accumulation rates had similar overall trends through the Holocene. Three of the highest peaks in chironomid production occurred during the early-to mid-Holocene, between 10.2-9.5 ka, 8.3-7.5 and 7.0-6.5 ka. The peaks starting at 10.2 and 7.0 ka correspond to relatively high values of organic AR. Between 6.5-4.0 ka, HC concentrations were the lowest of the core. Concentrations were slightly higher between 4.0 ka to 1.0 ka. A large peak in chironomid concentration and AR occurring at 1.6 ka is due to the very high production of *Corynocera oliveri*-type at that one level in the core. After 1.0 ka chironomid production decreased until 0.14 ka when chironomid AR increased again rapidly.

Chironomid composition

A total of 40 taxa were recovered from the KR02 sediment core (Figure 4). Taxa found in the KR02 core were similar to those found in a sediment core from Northern Victoria Island (Lake WB02, Fortin and Gajewski, 2010a [5]) and are typical of those found in cold, nutrient-limited Arctic lakes.

Before 9.9 ka, both cold- and warm-tolerant taxa were present in the sediment. Taxa from the subtribe Tanytarsina, including Tanytarsina-other and *Micropsectra* spp. (specifically *Micropsectra insignilobus*-type) (Francis et al. 2006; Larocque et al., 2006; Porinchu et al., 2009a) were the most abundant individuals during this period. All the dominant taxa found somewhere in the core were present during this time, except for *Abiskomyia* and *Pseudodiamesa*, both of which are cold-tolerant taxa (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007, Porinchu et al., 2009a) and warmer water *Psectrocladius (Psectrocladius)*-type (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a).

From 9.9-7.5 ka, cold-tolerant *Paracladius* and *Sergentia,* which is either cold tolerant or is most abundant in intermediate conditions, were found in low abundance (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a). The chironomid assemblages were dominated by the warm and intermediate-tolerant taxa of the subtribe Tanytarsina (Tanytarsina-other, *Micropsectra* spp. *Paratanytarsus* spp. and *Tanytarsus* spp.) which made up on average 50% of the total assemblage. *Paratanytarsus* spp. was present throughout the record, but reached highest abundances in the early Holocene. *Corynocera oliveri*-type was more abundant in this time period than at any other time in Holocene, with the exception of one large peak at 1.6 ka. *Chironomus anthracinus*-type, which is a taxon that prefers moderate to warm temperatures (Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a), also disappeared from the assemblage at this time and only returned in low abundance at 8.4 ka. Neither *Abiskomyia* nor *Pseudodiamesa*, two taxa with very cold mean July air and water temperature optima, were part of the assemblage during this period. However, other taxa tolerant of cold to moderate temperatures, such as *Parakiefferiella nigra*-type (Barley et al., 2006; Brooks et al., 2007) and *Heterotrissocladius* spp., were more abundant during this time than at any other point in the core (Barley et al., 2004; Gajewski et al., 2005; Francis et al., 2006; Larocque et al., 2006). Rarer taxa such as warm-tolerant *Procladius*–type (Gajewski et al., 2005; Barley et al., 2006; Francis et al., 2006; Brooks et al., 2007; Porinchu et al., 2009a) and *Psectrocladius (Psectrocladius)*-type were also present in the core.

A change in chironomid composition occurred from ~7.5-6.5 ka, when warm-tolerant taxa were replaced by cold-water taxa. Several taxa, including *Micropsectra* spp. and Tanytarsina-other decreased in abundance as *Paracladius* and *Sergentia* increased. *Chironomus anthracinus*-type, which had been absent from the sediment between 9.9 and 8.5

ka, became more abundant and peaked at ~7.1 ka. This taxon has been found in sediment assemblages after large disturbances, even if under sub-optimal conditions (Brooks et al., 2007).

From 6.5 to ~4.0 ka, the warm-tolerant taxa all but disappeared from the assemblages, being initially replaced by the cold-water taxon *Paracladius*, the cold- to moderate-tolerant *Sergentia* and moderate- to warm-tolerant *Zalutschia* spB (Barley et al., 2006; Francis et al., 2006; Porinchu et al., 2009a). These taxa dominated until ~6.0 ka when *Abiskomyia* entered the assemblage, in low relative abundance for the first 1000 years, but then dominating from 4.8-4.0 ka with relative abundance as high as 60%. At 5.7 ka, *Cricotopus /Orthocladius* spp. was abundant; it subsequently decreased until 3.3 ka. *Cricotopus /Orthocladius* spp. appear to be cold to moderate temperature tolerant (Barley et al., 2006; Francis et al., 2006, Porinchu et al., 2009a), however this group integrates a large number of presently undifferentiated taxa whose respective temperature optima may be different. *Chironomus anthracinus*-type abruptly decreased in relative abundance after 7.1 ka but remained on average 10% of the assemblage until ~0.7 ka.

After 4.0 ka, the relative abundance of *Abiskomyia* decreased and the cold-tolerant taxa that were present in the core prior to the dominance of *Abiskomyia* once again increased in abundance. *Paracladius* became the most abundant taxon in the core for the remainder of the Holocene. *Sergentia*-type was also an important taxon at this time. Although in lesser relative abundance, *Pseudodiamesa* reached maximum values during the time period from 4 ka and 1.6 ka. *Abiskomyia* reappeared in higher abundance between 2.0-1.8 ka, as did *Pseudodiamesa*, replacing *Paracladius*.

After 1.6 ka the warm-tolerant taxa present in the assemblage during the early-Holocene again increased in abundance, especially *Corynocera oliveri*-type, which at 1.6 ka represented 55% of the assemblage. Taxa from the subtribe Tanytarsina became more abundant, as did the rarer warm-tolerant *Psectrocladius (Psectrocladius)*-type and *Procladius*. Colder-tolerant taxa such as *Abiskomyia*, *Pseudodiamesa* and *Paracladius* decreased in abundance or simply disappeared from the assemblage at this time.

Between 1.0-0.14 ka, *Abiskomyia* became far more abundant and *Pseudodiamesa* reappeared in the assemblage, although in low relative abundance, while the warmer taxa which had appeared around 1.6 ka decreased to very low values. As of 0.14 ka the relative abundance of *Abiskomyia* decreased as *Paracladius* and *Sergentia* increased. All of the warmer taxa that were present during the early-Holocene, with the exception of *Procladius*, were still present in the assemblage, although their relative abundances did not significantly increase in the recent sediments.

Ordination of the chironomid assemblages

The first two components of a principal components analysis (PCA) used to summarize the trends in chironomid assemblages and sediment parameters through time explained 25% and 13% of the total variance (Figure 5). Tanytarsina-other, *Micropsectra* spp., *Parakiefferiella nigra* and *Heterotrissocladius maeaeri* had positive loadings on the first axis whereas *Abiskomyia*, *Pseudodiamesa*, *Paracladius*, *Sergentia* and *Zalutschia*-type B had negative loadings on this first axis.

The first component sample scores were highest and relatively constant up to 8.1 ka and then decreased until the most recent sediment (Figure 6). The sample scores for the second component increased until 5 ka and then declined again until ~3.5 ka, although they remained positive. Between 3.5 ka and 2.0 ka, the scores of the second component fluctuated just above zero, then became negative at 2.0 ka. Scores were lowest at ~1.2 ka, rising slightly since that time.

Interpretation of biological paleo-production

The pollen, diatom and chironomid concentrations and accumulation rates, interpreted as production records, all indicate higher production prior to 6.5 ka although diatom and BSi concentrations show some differences due to changes in species compositions (Podritske and Gajewski, 2007; Peros and Gajewski, 2008; Figures 3 and 7). Accumulation rates and concentrations of all three groups tend to be lower in the past 6.5 ka, although there were coherent variations even at these low values in the mid- to late-Holocene (Figure 7). All three groups show synchronous peaks in production at ~7.0 ka and again in the recent sediment, and the aquatic organisms show elevated values relative to the previous millennia between ~4-1 ka.

Paleoenvironmental reconstructions

Both chironomid-based WAPLS and MAT methods produced similar long term trends in July temperature reconstructions, although the MAT technique generally predicted on average 0.9°C warmer temperatures than the WAPLS technique (Figure 6). The sample specific error estimates were on average 2°C (+/- 0.1°C) and 2.4°C (+/- 0.15°C) for the WAPLS and MAT respectively. The early-Holocene, from 10.2 ka to ~6.7 ka, was indicated to be the warmest period, with temperatures between 9.6 and 11.7°C and 10.9 and 12.7°C for the WAPLS and MAT reconstructions, respectively. This was followed by a long-term decrease in July temperatures until 1.6 ka. The chironomid-based MAT reconstructed large temperature fluctuations during this time, rising from 6 to 11°C in the span of only 500 years, whereas the WAPLS model reconstructed a more gradual decrease in temperature from 5.7-4 ka followed by a more stable cool period from 4.0 ka to 1.6 ka. Temperatures rose rapidly at 1.6 ka, remaining relatively warm until ~ 1.0 ka; this is especially noticeable in the MAT reconstruction. This period was followed by an abrupt transition into a cool period, reaching similar cold temperatures as those experienced around 2 ka. From 0.14 ka to recent times temperatures rose slightly. The chironomid-derived WAPLS and MAT models generated average temperatures for the 5 samples between 1971-2000 of 7.7°C and 8.1°C for the WAPLS and MAT models, respectively, compared to Ulukhaktok (Holman) July air temperature normals from 1971-2000 of 9.2°C (1971-2000 normals, Meteorological Survey of Canada, 2006).

A pH reconstruction based on sediment carbonate and BSi weight% (Fortin and Gajewski, 2009 [2]) indicates oscillations in lake water pH, with peak values of more alkaline periods prior to ~ 9.9 ka, between 8.0 and 7.5 ka and again between 4.5 to 5.5 ka. Lake water pH inferred for the most recent sediment was 7.1, which is comparable to the pH of 7.3 which was measured at the lake at the time the core was collected.

Discussion

Low frequency climatic change during the Holocene

The chironomid-based mean July air temperature reconstruction indicates a warmer early- to mid-Holocene prior to ~7.5 ka and a subsequent long term cooling marked by a number of warming and cooling events of differing duration. The chironomid-derived mean July air temperature, supported by increases in both organic and BSi production and AR, indicated a warming over the last 140 years. Although the sample specific errors for the air temperature reconstructions are relatively large, the temperatures estimated for the early Holocene (before ~7 ka) remain significantly higher than those estimated for the mid Holocene (5 to ~1.6 ka), and those estimated after 1 ka. Although the broad-scale trends in production indices are coherent with the chironomid-based reconstruction, higher frequency variability is not easily associated with the inferred temperatures.

A pollen-based mean July air temperature reconstruction also shows a similar pattern (Figure 6) with a long-term increase in relative abundance of pollen taxa characteristic of high-Arctic vegetation starting around 8.0 ka and continuing throughout the Holocene (Peros and Gajewski, 2008). Interpretation of the diatom record is less straightforward, as factors such as within-lake or post-depositional dissolution may have affected the diatom assemblages and concentrations present in the sediment, most notably in the bottom half of the core (Podritske and Gajewski, 2007; Figure 7).

Sediment organic and BSi AR and weight % were generally lowest in the warmer early-Holocene (notably 9.5-8.1 ka) and highest during the cooler late Holocene (after 4 ka). Similar organic profiles, where organic content increases in the sediment through the Holocene, are found in the sediment records of Lake PW03, Prescott Island and Lake RS29, Somerset Island in Nunavut (Finkelstein and Gajewski, 2007b; Paull, 2008). It is unclear why organic matter (AR and weight %) is increasing at these sites through the Holocene, as numerous proxy records clearly indicate a long-term cooling throughout the region (summarized in Gajewski and Atkinson, 2003; Kaufman et al., 2004). These broader trends in organic accumulation may be related to lake ontogeny rather than a response of the ecosystem to direct external forcing (Deevey, 1984; Battarbee et al., 2005; Anderson et al., 2008). The organic matter building up through time in the lacustrine system could be the result of a number of factors such as positive ratios of production vs. diagenesis of the organic matter, or changes in the basin morphometry through time. The accumulation of organic matter in the sediment would therefore not be due to simply to climate-induced increases in lacustrine ecosystem productivity but rather to the natural evolution of the lake as it ages (Deevey, 1984). Although it is not clear that this process applies in these oligotrophic lakes with short growing seasons, it does remain one working hypothesis to explain the building up of organic matter in these systems.

Within this long-term increasing trend of organic matter at Lake KR02, there are periods of relatively higher organic production, especially noticeable in the organic percentage and AR curves at 10.5-9.5 ka, 7.2-6.5 ka, 4.0-1.7 ka. These periods correspond to similar increases in the chironomid, pollen and diatom concentration and AR curves, as well as BSi percentages (Figure 7). These smaller-scale variations in AR are reflecting increases in organic production by these and presumably other organisms in the watershed and the lake, and are a consequence of changes in environmental conditions superimposed on the build-up through time of organic matter in the system.

The chironomid- and pollen-based mean July air temperatures at Lake KR02 both showed a cooling trend through the Holocene (Figure 6). The chironomid-based temperature reconstruction also shows transitions at the same time as does the production indices, including that of pollen production, although this is not as evident in the pollen-based July temperature reconstruction. However, the range of predicted temperatures based on the pollen record is much narrower than that of the chironomid-based temperatures, and the pollen-based temperatures were systematically cooler, up to 5°C, than those based on chironomid assemblages (Figure 6). Francis et al. (2006) and Briner et al. (2006) noted that chironomid-inferred July air temperatures for sites on Baffin Island were comparably higher than those based on pollen. These authors suggest that their pollen records, which were shorter than the chironomid records, may not have actually "captured" the highest temperatures of the Holocene thermal maximum (HTM). However, this is not the case for Lake KR02, as the differences at Lake KR02 between chironomid- and pollen-based mean July air temperatures continue into the most recent sediments, with chironomid-inferred temperatures on average 2°C warmer than the pollen-based ones. The mean July air temperature normal of 9.2°C, taken from the Ulukhatok (Holman) meteorological station, is closer to the chironomid-inferred mean July air temperatures for this same period (7.7° and 8.1°C, based on the WAPLS and MAT respectively) than the values of 5.5°C (WAPLS) and 5.8°C (MAT) predicted from the pollen. To better understand this difference in estimated temperatures through the Holocene at Lake KR02, we looked at the geographical distribution of the modern analogues chosen for both the pollen and chironomid records. The fossil pollen record most closely resembles (best analogues) modern assemblages from Boothia Peninsula, western Victoria Island and Somerset Island, all located between 70 and 73° latitude, in the low to middle Arctic. The chironomid fossil assemblages have close analogues from northern British Columbia and the southern Yukon for the early-Holocene and from Tuktoyaktuk, Boothia Peninsula and Somerset Island for the middle- to late-Holocene. Thus, the chironomid fossil record has modern analogues located further south than the pollen fossil assemblages, which explains the inferred warmer temperatures. The distribution of sites for both the pollen and chironomids have similar northern reaches, however the pollen data used by Peros and Gajewski (2007) does not extend further south than Boothia Peninsula, since boreal forest pollen would clearly not be chosen as acceptable analogues for the tundra pollen assemblages in the KR02 core. Although this analysis explains why the temperature reconstructions are different, it does not explain why chironomid assemblages find good analogues so far south. It may be due to the lack of chironomid samples from parts of the Canadian Arctic, so best analogues are found to the south, where widely distributed chironomids are living. Alternatively, it may be that Arctic plants, also widely distributed, are excluded by competition from the boreal zone, although they may be able to tolerate the warmer conditions. Other hypotheses could be offered, but this difference in reconstructions between different groups of organisms requires further study, and this exercise shows that we need a better understanding of the biogeography of both groups to resolve this issue.

Terrestrial and aquatic responses to high-frequency climatic changes

Prior to 10.2 ka, magnetic susceptibility values were very high, during a short period of ~300 years immediately following the formation of the lake basin. High values of MS immediately after deglaciation have been found in other sediment cores and can be associated with lake sediment receiving glacial outwash (Finkelstein and Gajewski, 2007b) and rapid inwash from slopes surrounding the lake. Chironomid species richness is very high in this portion of the core, implying rapid colonization of the site by chironomids and the immediate establishment of the species pool in the lake. This indicates a rapid dispersal of chironomids to northwestern Victoria Island at time when the Laurentide ice sheet was to the south, implying either long-distance transport or movement to the site from areas far to the south, or an origin from refugia somewhere in the western Arctic.

Between 10.2 ka to ~7.5 ka, the warmest period in western Victoria Island, the chironomid assemblages were dominated by warm-tolerant taxa and chironomid production and accumulation rates were higher than at any other time. Chironomid-based temperature estimates were up to 4°C warmer than the temperatures inferred for the most recent 140 years. Closest modern analogues for the fossil chironomid assemblages during this time were found in northern British Columbia, southern Yukon and the Tuktoyaktuk Peninsula. Peaks in chironomid production in the earlier Holocene, between 10.2-9.5 ka and 8.3-7.5 ka, are largely due to increases in production of the warm-tolerant taxa. These peaks were synchronous with those of the pollen concentration and pollen accumulation rates and with increases in the organic AR and percentages in the lake at 10.2 ka and to a smaller extent at 8.3 ka (Figures 3 and 7).

A small peak in diatom production also occurs between 9.9-9.6 ka (Figure 7a). However, despite the enhanced production in the chironomid and pollen data, diatom concentrations remained very low between 8.3-7.5 ka. Podritske and Gajewski, (2007) observed significant valve fragmentation and very low overall diatom concentrations prior to 7.0 ka (Figure 7). They proposed three hypotheses for the presence of diatom-free zones during these times: dissolution, dilution due to increased runoff, and cool temperatures. Given the high values of both pollen and chironomid AR during periods of low diatom concentrations and the warm reconstructed temperatures, we can now dismiss cool temperatures (which presumably would have led to the lake being ice covered for long time periods) as a possible cause. There is no evidence for valve dilution in the sediment due to increased runoff as a potential cause either, as the concentrations and AR of pollen and chironomids remained high during these times of low diatom concentrations. This leaves dissolution as a probable cause of the low values, perhaps due to an increase in lake water pH causing post-depositional dissolution, or by the dissolving of the diatom in the water or sediment surface due to low silica concentrations in the water. Podritske and Gajewski (2007) also note important valve fragmentation between 8.5-8.2 ka and 7.6-7.0 ka (Figure 7) and indeed the inferred pH profile (Figure 6), based on sediment carbonate and biogenic silica weight %, indicates highest pH values corresponding to the times of valve fragmentation and very low diatoms concentrations. Diatom dissolution can occur at higher pH (e.g., Ryves et al., 2006) and the diatoms which were found in the dissolved areas of the core were alkalophilic taxa (Podritske and Gajewski, 2007). However, the mechanisms behind diatom dissolution are not yet well understood; therefore the validity of this third hypothesis needs to be further explored.

Kaufmann et al. (2004) interpreted the Holocene Thermal Maximum (HTM) as having occurred in the western Arctic between 8.9 ± 2.1 ka and 5.9 ± 2.6 ka. We are now able to better constrain this period between 9.9 to 7.5 ka for this site on western Victoria Island, as all of the proxies in this well-dated core concur to indicate this is the warmest period. At Lake WB02 on Northern Victoria Island, chironomid production was also highest in the early-Holocene (Fortin and Gajewski 2010a [5]). Chironomid records from Lake CF3 on Baffin Island indicate temperatures ~ 5°C warmer between 10 and 8.5 ka (Briner et al., 2006) which is comparable to the timing of the warming at KR02.

A significant transition occurred at Lake KR02 between 7.5 and 6.5 ka, which is interpreted as a shift towards a cooler climate. This transition is seen in the chironomid assemblages, where a community dominated by warmer-tolerant taxa was replaced by one dominated by colder-tolerant taxa, for example, the near disappearance of warm-tolerant taxa from the Tanytarsina subtribe and the appearance of cold-water *Paracladius* and cold to moderate temperature *Sergentia* taxa (Figure 4). Similarly, the pollen assemblages are also interpreted as indicating a cooling. Based on the chironomid record it seems that this transition can be divided into three parts. As the cooling began (~7.5 ka), the warm-water taxa decreased in relative abundance quite abruptly and were initially replaced by *Chironomus anthracinus*-type. *Chironomus anthracinus*-type is a taxon which is usually found in profundal areas in lakes. It was present in the earliest assemblages, but was later reduced in abundance, perhaps because it was unable to compete for food or other resources with the other profundal taxa *Micropsectra* spp. and *Heterotrissocladius* spp. (Larocque et al., 2006, Brook et al., 2007) also present in the core in the warmer early-Holocene. Changing environmental conditions, as quantified in the chironomid- and pollen- (MAT) based air temperature reconstructions, are associated with a decrease in abundance of *Micropsectra* spp. and Tanytarsina-other, which were rapidly replaced by *Chironomus anthracinus*-type. The high abundance of this taxon at this time may be indicative of a large change occurring in the environment. *Chironomus anthracinus*-type was also present in the sediment record of Lake WB02 in northern Victoria Island at roughly the same time (Fortin and Gajewski, 2010a [5]), which for that region also corresponds to the timing of a major change in the chironomid assemblages. Colder-tolerant taxa quickly took over and dominated the assemblage. These cold-water taxa became so productive at ~6.9 ka that there was a spike in overall chironomid AR and concentrations, and this during an inferred cool period. Similar spikes are seen in the pollen and diatom production. These increases in production appear to be the ecosystem response to *changes* in climatic conditions, and are not due to an amelioration of environmental conditions, as climate in fact appears to be cooling at this time. This transition coincides with the disappearance of the Laurentide Ice Sheet to the south, beginning with the collapse of the ice sheet in the region that today is Hudson Bay around 8.2 ka, to the final melting of the ice in northern Québec around 6 ka (Dyke, 2004).The atmospheric circulation changed at that time, leading to a cooling in the Arctic following a period of warm air transport to the Arctic.

The chironomid- and pollen-based mean July air temperatures between 6.4-4ka remain cooler than those reconstructed prior to 7.5 ka. The chironomid assemblages during this time resembled the assemblages found in low and middle Arctic lakes from Tuktoyaktuk, the Boothia Peninsulas and Somerset Island. The chironomid-inferred air temperature profile, however, shows more variability than the pollen-based reconstruction, although the low concentrations of head capsules in the sediments of this time make the reconstructions less reliable. Terrestrial and aquatic production remained low during this cooling and even though there was a decrease in organic AR and percentages when compared to the values at ~6.8 ka, values do remain higher than those in the early-Holocene. *Abiskomyia* may have arrived on Victoria Island at ~6.0 ka, as it entered the assemblage at both Lake KR02 and Lake WB02 (Northern Victoria) at this time, dominating the assemblages at both lakes in the later Holocene (Fortin and Gajewski, 2010a [5]).

The period between 6.5 and 4 ka corresponds to a period with the fewest modern analogues. This suggests that the modern dataset used may not have contained sufficient modern sites with colder air temperatures (see Fortin and Gajewski, 2010a [5]). The cooling observed at KR02 in the mid-Holocene (Figure 6) is also observed in records from the Agassiz Ice core on northern Ellesmere (Fisher et al., 1995), as well as inferred from decreases in chironomid, pollen and/or diatom production in lakes from northern Victoria Island, northern Boothia Peninsula, Somerset Island and Prince of Wales Island (Gajewski, 1995; LeBlanc et al., 2004; Finkelstein and Gajewski, 2007b; Zabenskie and Gajewski, 2007; Fortin and Gajewski, 2010a [5]).

Another environmental change occurred at 4.0 ka, which triggered an increase in production of aquatic organisms, as well as an increase in sediment organic content extending over the next two thousand years. After 4.0 ka, the chironomid assemblages were still dominated by the same cold-water taxa as before, but warmer tolerant taxa which were present in the early-Holocene returned to the assemblages, albeit in low relative abundances. Although interpretation of the chironomid assemblages indicates large changes between 4.0 ka and 2.0 ka, the quantitative reconstructions do not; they indicate continued cool conditions, as does the pollen-based mean July air temperatures record. The chironomid-inferred temperatures indicate more or less constant temperatures between 4 ka and 2 ka with some high frequency variability, whereas the pollen-based air temperatures show a continuation of the same cooling trend which had been occurring since ~7.5 ka.

After ~2.5 ka, both the chironomid-based and pollen-based temperature reconstructions (especially seen in the MAT based reconstructions in both cases) indicate an abrupt cooling event. Temperatures quickly rose around 1.6 ka and remained high until ~1.0 ka in both the pollen and chironomid reconstructions. From 1.6-1.0 ka the chironomid community resembled those assemblages currently found in northern British Columbia and warmer lakes of the Tuktoyaktuk Peninsula. Similarly, diatom richness and production both increased at this time, as did the heterogeneity of the life strategies and living habitats of the diatom taxa found within the assemblages at this time (Podritske and Gajewski, 2007). Distinct changes in the diatom community also occurred between 1.4 and 0.95 ka. Inferred warming periods, said to correspond to the Medieval Warm Period (MWP), were noted as having occurred broadly between 1.5 and 0.6 ka in the central Arctic on Boothia Peninsula, Prince of Wales, Southampton Island and northern Victoria Island (Overpeck et al., 1997; Leblanc et al., 2004; Finkelstein and Gajewski, 2007b; Fortin and Gajewski, 2010a [5]; Rolland et al., 2009).

A cooling began around 1.0-0.85 ka. This is inferred from the chironomid record and temperature reconstruction, as well as by the diatom assemblage, diversity and production records. The chironomid assemblages during this time were similar to those currently found in the Middle Arctic. This cooling may correspond to the Little Ice Age (LIA) which was observed at roughly the same time as that of several diatom (Wolfe, 2003; LeBlanc et al., 2004) and pollen records (Finkelstein and Gajewski, 2007b) across the Arctic. Chironomid-based studies from Baffin Island (Briner et al., 2006; Francis et al., 2006) were unable to detect the LIA in their records, but a cooling was recorded in the midge record from Southampton Island between 0.6 and 0.3 ka (Rolland et al., 2008) and from southern Victoria Island between 0.9 and 0.3 ka (Porinchu et al., 2009b).

From ~0.14 ka, the pollen and chironomid-derived temperature reconstructions, as well as the production records of all three proxies seem to indicate a warming that continues until the most recent times. Organic and BSi percentages and AR also increased at this time. This post-Little Ice Age warming is now well documented across the Arctic (e.g., LeBlanc et al., 2004; Smol et al., 2005; Peros and Gajewski, 2008; Kaufman et al., 2009; Fortin and Gajewski, 2010a [5];). However temperatures inferred and measured for recent times at Lake KR02 remain up to 4°C cooler than those of the early- to mid- Holocene warm period.

Conclusion

Multi-proxy analyses of sediment cores provide a more complete understanding of past climatic conditions than those obtained from only one source. For Lake KR02 on western Victoria Island, interpretations of the pollen and diatom records included some discrepancies regarding the climatic conditions at this lake over the Holocene period. The chironomid data presented here for this lake were able, in part, to reconcile the differences between the pollen and diatom records, and also elucidate the climatic history of the lake. The early-Holocene prior to 6.5 ka was a warm period of high aquatic and terrestrial production. From 5.5 to 4 ka there was a cooling period, followed by change in environmental conditions at 4 ka and cool temperatures lasting the next two millennia. An abrupt warming occurs at 1.6 ka, followed by an abrupt cooling at ~1.0 ka and a final increase in temperature, starting at 0.14 ka through to recent times. Temperatures prior to 6.5 ka are the warmest for the Holocene. The climate as recorded at lake KR02 also corresponds to the climate inferred from independent records from other sites on Victoria Island and across the Arctic.

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Table 1 Radiocarbon dates, calibrated ages (cal BP, with base 1950AD), and calibrated ages ka (base of 2000AD). The date at depth of 404-407cm was not included in age depth curve

Lab code (Beta)	Depth (cm)	Conventional radiocarbon age yr BP	Calibrated 2σ range age yr BP	Median calibrated age yr BP	Age ka (before 2000 AD)	Material dated
Beta-199874	37.5-39.5	890 ± 40	710-920	815	0.865	bulk sediment
Beta-199875	70-73	1680 ± 50	1500-1710	1605	1.655	macrofossils
Beta-199877	208-209	3500 ± 40	3670-3870	3770	3.820	macrofossils
Beta-206009	241-243	4270 ± 40	4820-4870	4845	4.895	bulk sediment
Beta-199878	291-293	5760 ± 50	6430-6670	6550	6.600	bulk sediment
Beta-206010	314-317	6150 ± 50	6890-7200	7045	7.095	macrofossils
Beta-206011	333-335	7050 ± 50	7760-7960	7860	7.910	macrofossils
Beta-213872	349-351	8590 ± 40	9520-9570	9545	9.595	macrofossils
Beta-199879	362-364	8730 ± 60	9550-9920	9735	9.785	macrofossils
Beta-206012	404-407	18950 ± 170		rejected		bulk sediment

Table 2 ^{210}Pb dates (AD) and age (ka) for the KR02 sediment core. Years and ages are those of the bottom of each sample interval and were determined using a CRS model estimate

Depth (cm)	Year AD	Age ka (before 2000)
2.0-3.0	1995	0.005
3.0-4.0	1993	0.007
4.0-5.0	1990	0.01
5.0-6.0	1985	0.015
6.0-7.0	1980	0.02
7.0-8.0	1976	0.024
8.0-9.0	1972	0.028
9.0-10.0	1957	0.043
12.0-13.0	1934	0.066
14.0-15.0	1920	0.08
16.0-17.0	1901	0.099
18.0-19.0	1873	0.127
20.0-21.0	1837	0.163

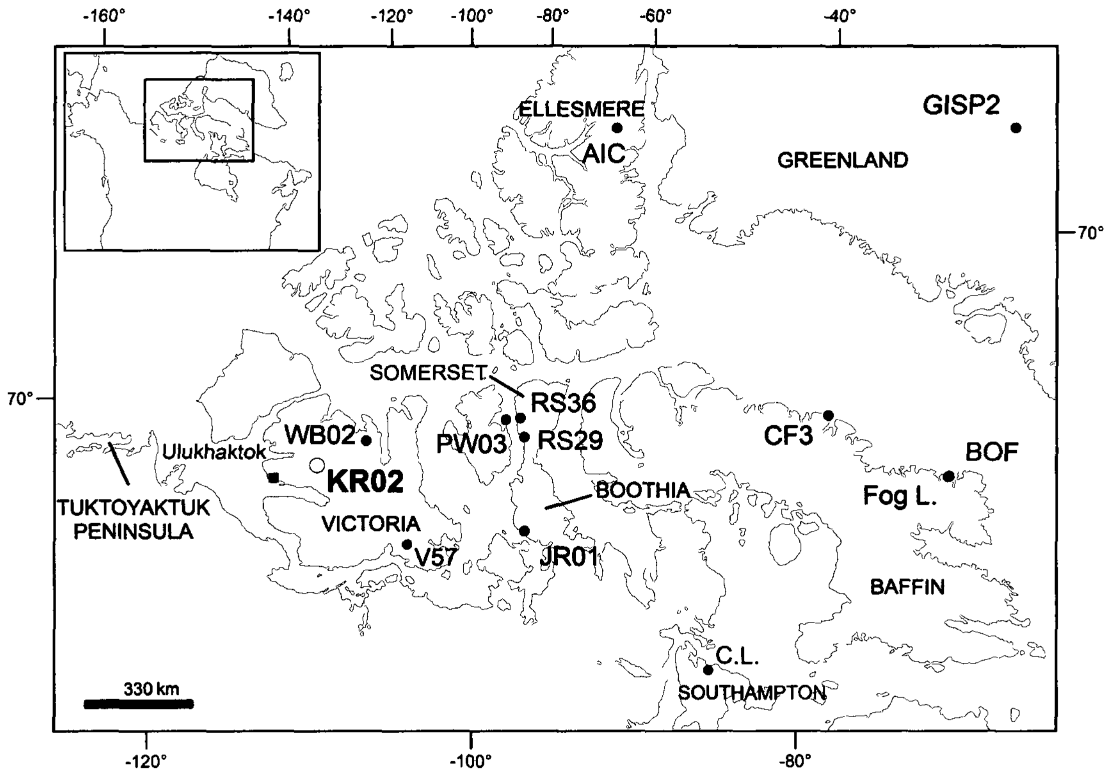

Figure 1 Map indicating location of Lake KR02 in the Northwest Territories. Lakes and ice cores referred to in the text are indicated: AIC Agassiz Ice Core (Fisher et al.,1995), GISP2 Ice Core (Alley, 2005), Lake CF3 (Briner et al., 2006), Lake PW03 (Finkelstein and Gajewski, 2007b), Lake WB02 (Fortin and Gajewski, 2010a [5]), Lakes RS29 and RS36 (Gajewski et al., 1995), Lake JR01 (diatoms: Leblanc et al., 2004; pollen: Zabenskie and Gajewski, 2007) and Fog and BOF "Brother of Fog" Lake (Wolfe, 2003; Francis et al., 2006), C.L. "Caribou" Lake (Rolland et al., 2008) and Lake V57 (Porinchu et al., 2009b)

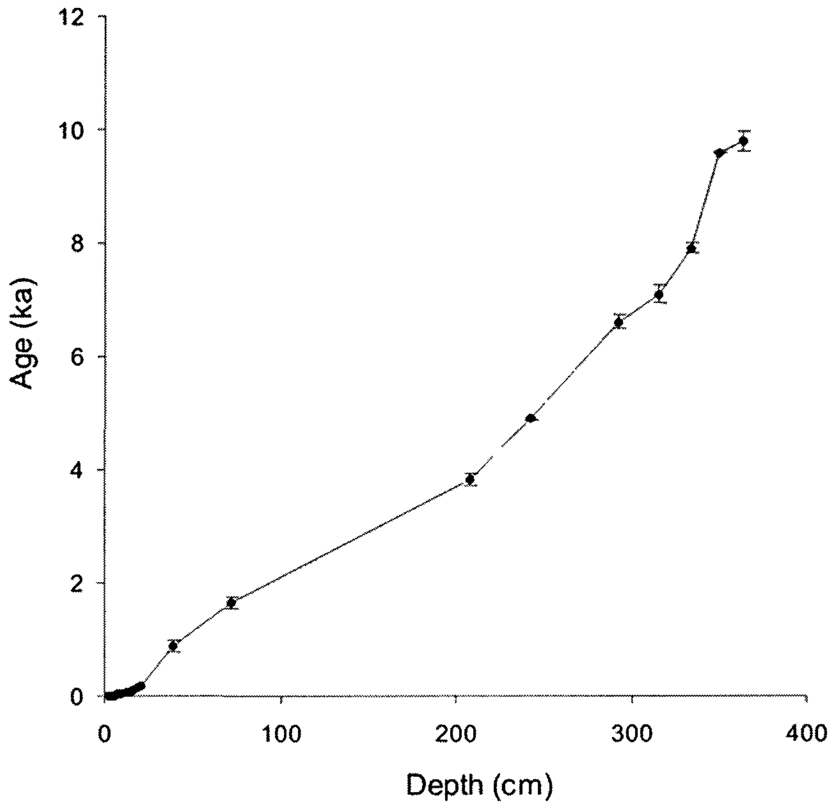

Figure 2 Age-depth curve for Lake KR02 based on ^{14}C and ^{210}Pb dating. All ages reported in ka with base AD 2000

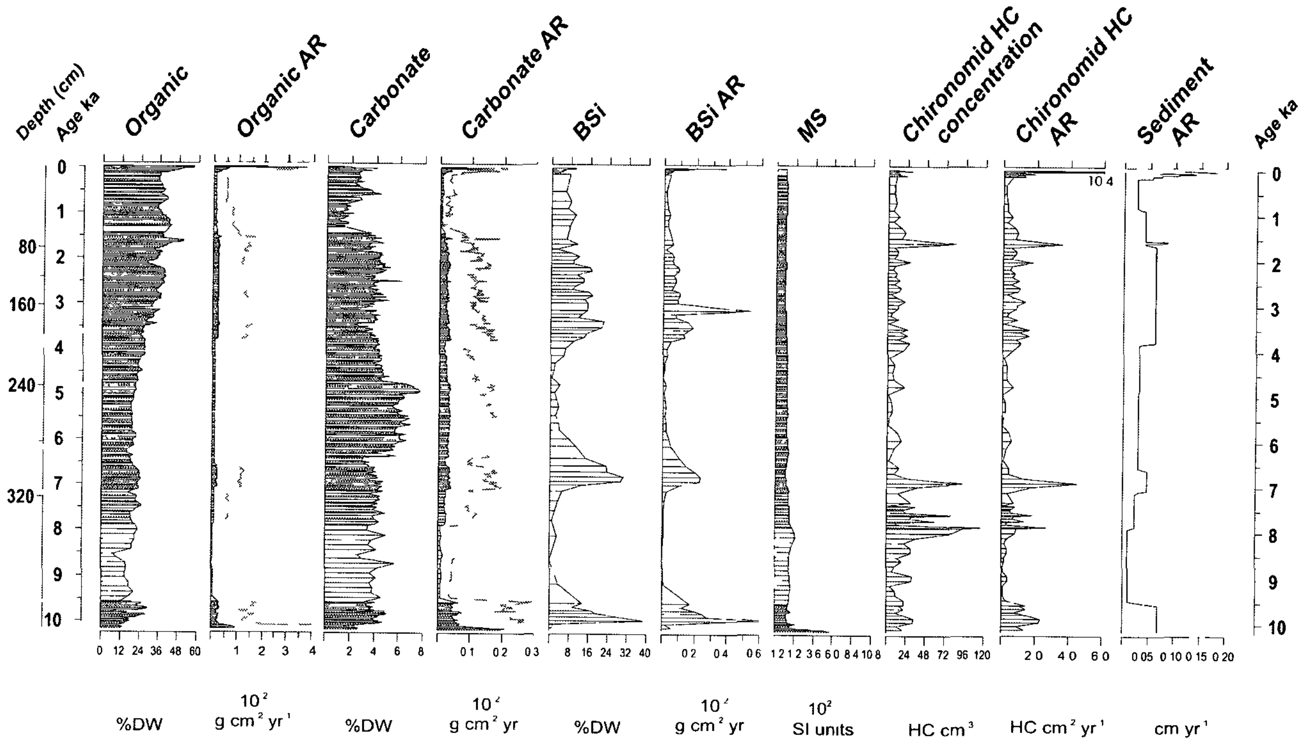

Figure 3 Biogeochemical sediment parameters of Lake KR02. All sediment proxies excluding magnetic susceptibility (MS) are reported in weight % or concentration and as accumulation rates (AR). Organic (LOI550) and carbonate (LOI950) plots each include a 5x exaggeration line (grey). The high values in the upper sediment of the chironomid head capsule (HC) AR were truncated and the value at 0.018 ka is indicated directly on plot. Ages are ka (1000 years) before AD 2000

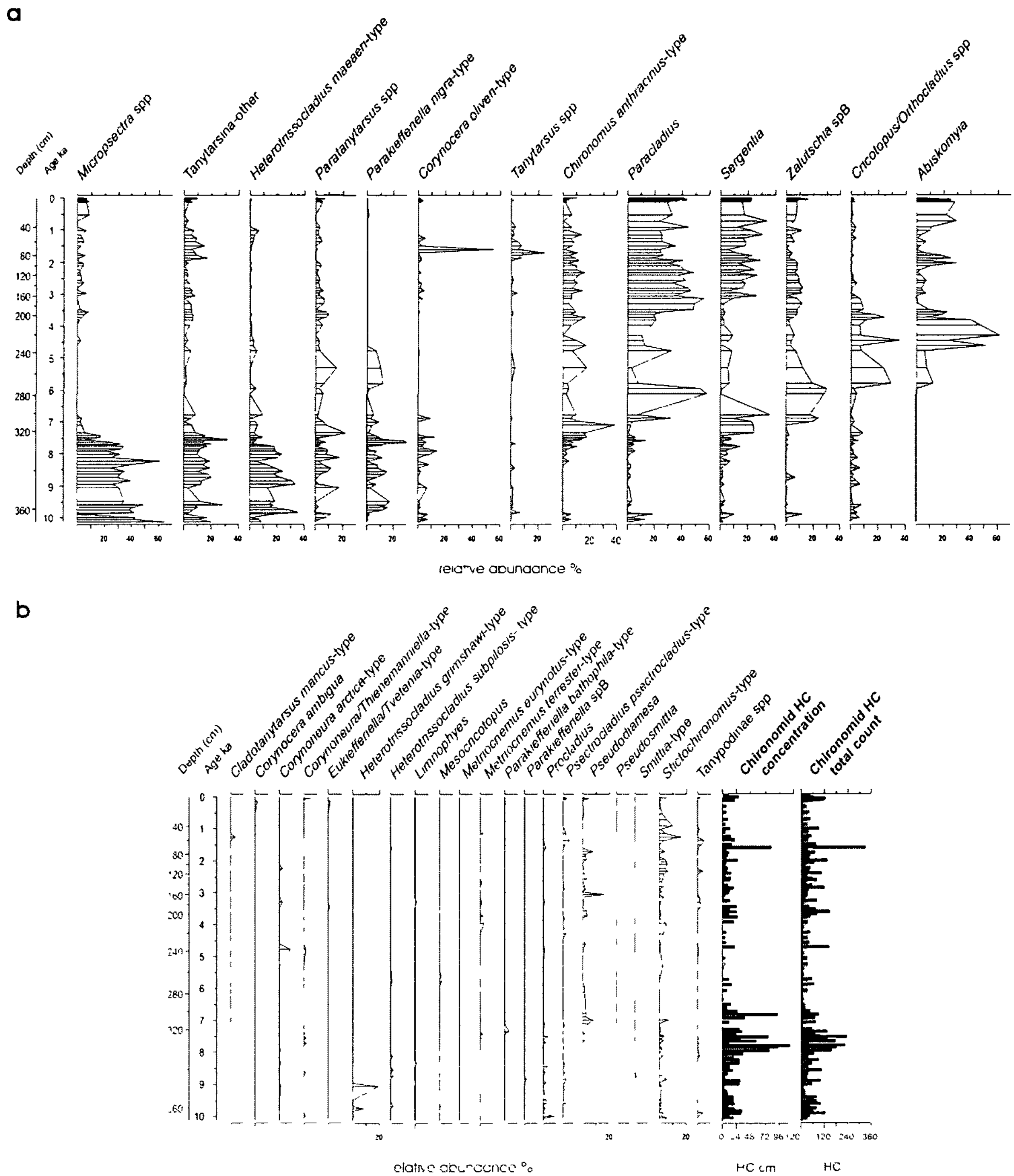

Figure 4 Time series plots of the relative abundances (%) of all of chironomid taxa present in Lake KR02 over the last 10,200 years. The (a) dominant chironomid taxa and (b) rarer chironomid taxa are presented only for levels with over 30 head capsules count sums. The dominant taxa are presented according to the order in which they appear in the core, whereas the rare taxa are presented alphabetically according to taxon name. Chironomid head capsule (HC) concentrations and count sums for all levels are also included. The light grey band indicates levels with less than 30 HC that were not included in the analysis, the dark grey band indicates the 9 levels with 30-40 HC that were also included in the analysis

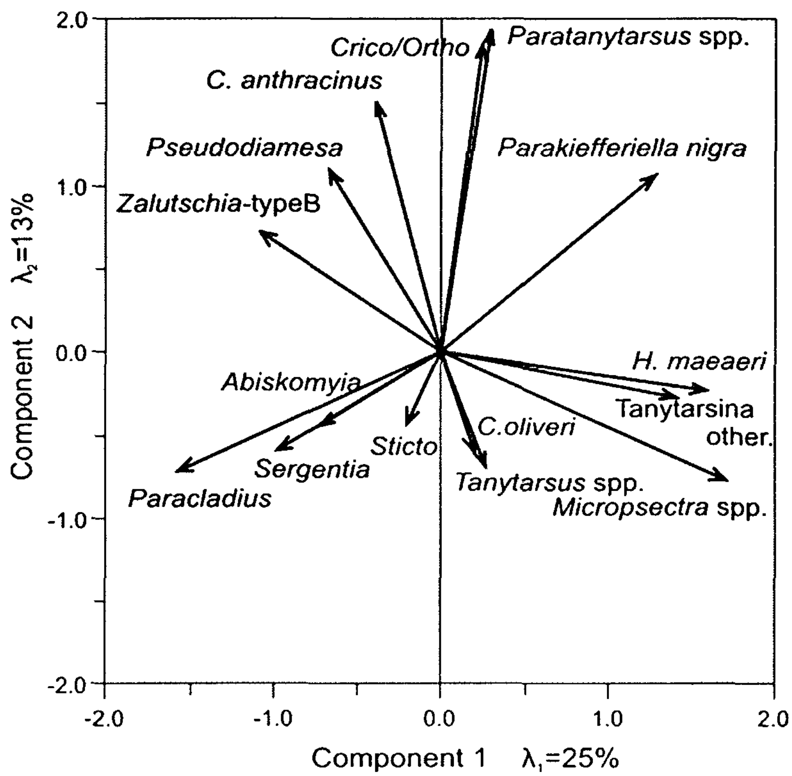

Figure 5 Principal component biplot of chironomid taxa (relative abundance %). Levels with more than 30 head capsules and only taxa with a mean relative abundance >1% averaged over all levels were included. *C. anthracinus=Chironomus anthracinus*-type, *C. oliveri=Corynocera oliveri*-type, *Crico/Ortho=Cricotopus / Orthocladius* spp., *H. maeaeri=Heterotrissocladius maeaeri*-type, *Strictos=Stictochironomus*-type

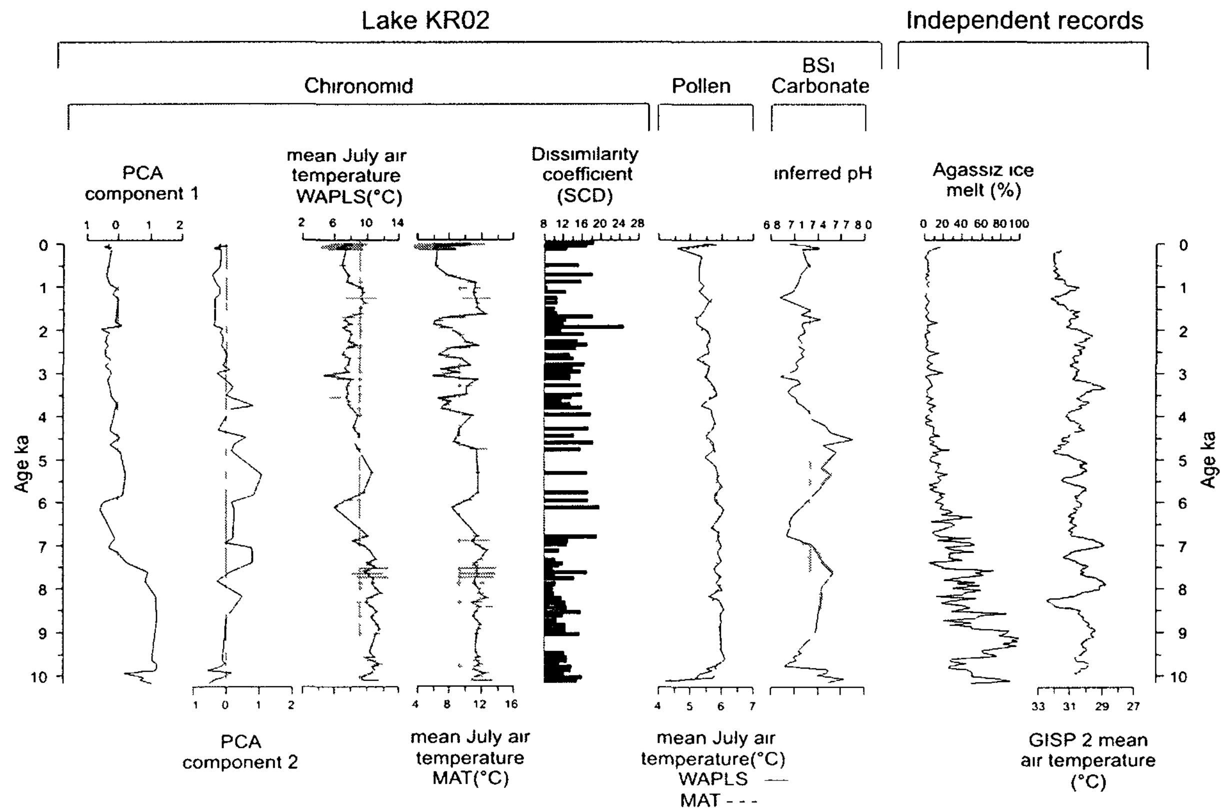

Figure 6 Lake KR02 chironomid-based PCA sample scores, chironomid and pollen (Peros and Gajewski 2008) inferred mean July air temperature (°C) and sediment BSi and carbonate inferred pH compared to independent climatic records of Agassiz ice melt % (Fortin and Gajewski, 2009 [2]; Fisher et al., 1995) and central Greenland mean July air temperatures (Alley, 2000). Both weighted average partial least squares (WAPLS) and modern analogue technique (MAT) generated temperature reconstructions are presented for the chironomid-based reconstructions. Horizontal grey lines represent the sample specific error estimates (°C). The vertical grey line at 9.2°C in the inferred temperature plots is the 1971-2000 July air temperature Normal for Ulukhaktok (Holman), the closest weather station, (Meteorological Survey of Canada, 2006). Squared chord distance (SCD) dissimilarity coefficient for the chironomid based MAT reconstruction is presented. Horizontal bars represent zones of inferred diatom dissolution (Podritske and Gajewski, 2007)

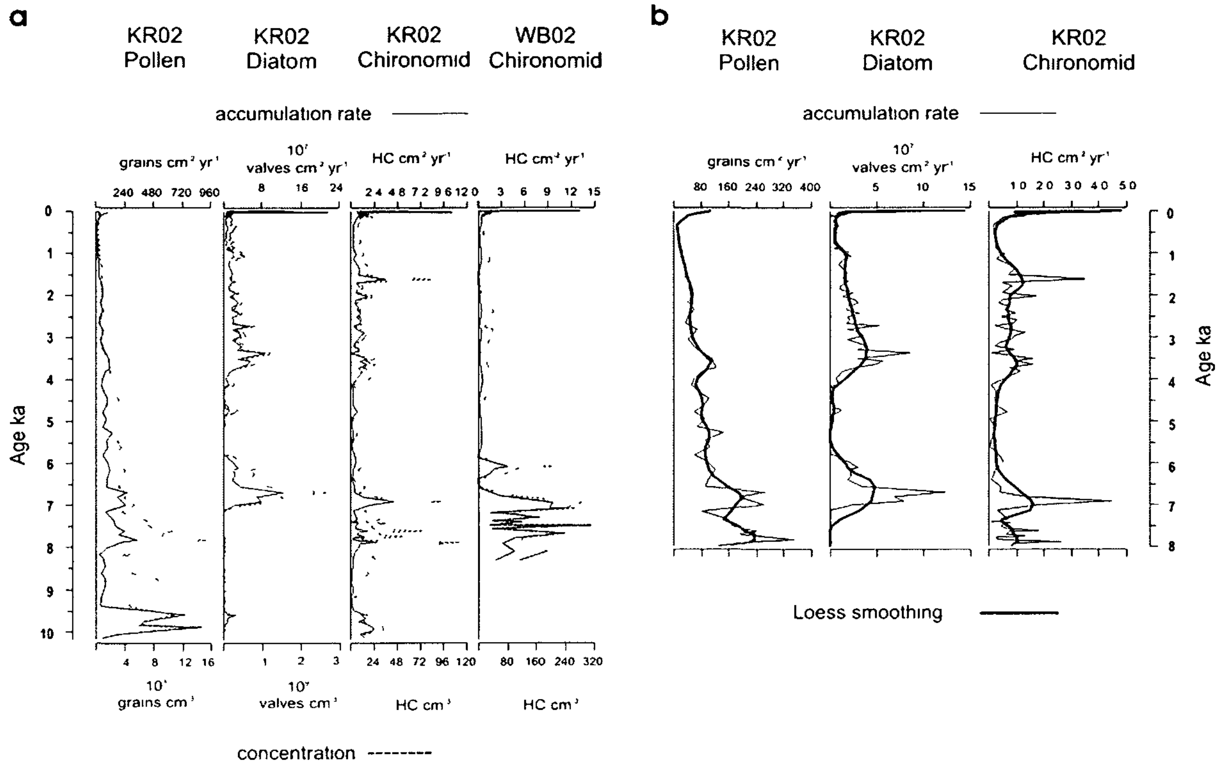

Figure 7 (a) Production profiles of pollen, diatom, and chironomid spanning the Holocene at Lake KR02 and production of chironomids at Lake WB02 in Northern Victoria Island (Fortin and Gajewski, 2010a [5]). Concentrations (dotted line) and accumulation rates (solid line) are both included. (b) Production profiles truncated at 8 ka of the pollen diatom, and chironomid proxies present in the sediment record of Lake KR02 are presented to illustrate the variability when values are low. A loess smoothing was added to each curve (thick line)

Chapter 7

Multiproxy paleoecological evidence of Holocene climatic changes on the Boothia Peninsula, Canadian Arctic

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Keywords: Chironomids, Holocene, Canadian Arctic, Boothia Peninsula, Climate Change, Quantitative Paleoclimate Reconstruction, Mean July air temperatures, Weighted Average Partial Least Square, Modern Analogue Technique, Diatoms, Pollen

Abstract

A high-resolution chironomid study of the sediments of Lake JR01 on Boothia Peninsula generated a reconstruction of mean July air temperatures for the last 7,200 years for this region. A large number of good analogues to the downcore fossil data were found in the modern samples used for calibration. Aquatic and terrestrial biological production, as indicated by chironomid, diatom and pollen concentrations and accumulation rates, as well as by sediment organic and biogenic silica content at Lake JR01 are highest in the early Holocene prior to 5.0ka. Overall production decreases through the mid- to late-Holocene until another increase during the last 0.15ka. Mean July air temperatures based on the chironomid record are warmest in the early Holocene, reaching up to 7.5°C, but cool until ~5.5ka, after which temperature remains relatively stable at approximately 6.0°C until 1.0ka. At 1.0ka a three-part cooling occurs, which coincides with the timing of the Little Ice Age seen in other regions. Evidence of the warmer early Holocene, colder mid- to late-Holocene and Little Ice Age is also present in Lake JR01's pollen and diatom records. Although biological production increased in the last 150 years, as did the temperatures reconstructed from the pollen record, the chironomid-based temperature profile does not infer a warming during this time. Temperatures reconstructed using both pollen and chironomid records indicate that the early Holocene remained warmer than the last 0.15ka, up to 3°C warmer based on the chironomid fossil assemblages.

Introduction

Changes in lake sediment composition provide information regarding changes in the lake's environmental conditions through time. For example, sediment organic and biogenic silica content can be used as a proxy for lake primary production (Fortin and Gajewski, 2009 [2]). Fossils preserved in the sediment, such as pollen grains, diatom valves and chironomid head capsules provide insight into how climate may have affected a lake's environment through time. Changes in the production and accumulation of these fossilized organisms can be used to qualitatively assess the impact of climatic changes on these organisms from different trophic levels if independent records of past climate are available; alternatively, changes in the species composition of these proxies can be used to qualitatively infer environmental change through time. To develop quantitative records of past conditions, the modern relationship between the particular proxy and the environment must first be calibrated using an inference model, which is then applied to the downcore proxy data. Multiproxy studies are even more important, since the different lines of evidence of past climatic conditions provided by each proxy can be used in comparison to one another, thus providing a much more comprehensive picture of the effect of climatic change on the lake ecosystem through time.

In this study we examine the climatic history over the last 7.2ka years of Lake JR01 (unofficially named), located on Boothia Peninsula in the southern Canadian Arctic, using a multi-proxy approach. Little is known regarding Holocene climatic conditions in this region (LeBlanc et al., 2004; Zabenskie and Gajewski, 2007). We focus our attention on the chironomids preserved in the sediment of Lake JR01, by generating both qualitative inferences regarding the production profiles of this lake, as well as a chironomid-based mean July air temperature reconstruction. Alternate inference models and reconstruction techniques are used to estimate past temperatures, and the differences are assessed and compared to previously-published pollen and diatom analyses of the lake. It will be shown that, despite some inconsistencies between the various records, the biological, physical and chemical proxies at Lake JR01 indicate that environmental conditions were warmer and that overall lake production was higher prior to 5.5ka than they are currently.

Study site

Lake JR01 is located in southern Boothia Peninsula in the middle Arctic (Figure 1; 69°54'N, 95°4.2'W, 120-m.a.s.l., 5.4m deep). This small lake (0.7 by 0.03km) is underlaid by Precambrian Shield and carbonitic bedrock (Dyke, 1984) and is surrounded by prostrate dwarf shrubs, and herb tundra (CAVM, 2003). Two small streams that run through sedge meadows drain into the lake. Water chemistry indicates that this lake is oligotrophic (TP=0.04 mg l^{-1}) and circumneutral to basic (pH=8.1) (Hamilton et al., 2001; Leblanc et al., 2004). Based on the 1995-2009 environmental data from the nearest weather station in Taloyoak (70 km distant), mean July air temperature in this region is 8.6°C and mean total July precipitation is 23.37mm (Environment Canada, 1994) Deglaciation in this area occurred around 9.5 ka, BC (Dyke, 2004).

Methods

A sediment core measuring 485cm, collected from the central part (5.84m deep) of ice-covered Lake JR01 was used for this study. Diatom and pollen analysis were previously conducted on this same core (Leblanc et al., 2004; Zabenskie and Gajewski, 2007).

The core was collected using a Livingston piston corer (5cm diameter) and the top 80cm was collected in a clear plastic tube attached to the drive rods to preserve the sediment water interface. The top 20cm was extruded in the field at 0.5cm intervals. The remaining sediment was wrapped in plastic wrap and aluminum foil and stored at 4°C.

Continuous measures of magnetic susceptibility and sediment loss-on-ignition, at one or 0.5 cm intervals were reported in Zabenskie and Gajewski (2007) and followed standard methods (Dean, 1974; Heiri et al., 2001). For our study, sediment biogenic silica was measured every 0.5-2cm downcore using 0.5cm^3 samples and a wet alkaline digestion technique (1% Na_2C0_3 base and reduced molybdosilic acid spectrophotometry) (De Master, 1981; Conley, 1998; Conley and Schelske, 2001).

Radiocarbon and ^{210}Pb dates were reported in Leblanc et al. (2004) and Zabenskie and Gajewski (2007) (Table 1). Three age models - a loess smoother, a spline function and linear interpolation - were used with the ^{210}Pb and calibrated ^{14}C dates to evaluate the influence of the age-depth model on the accumulation rates of sediment proxies (Figure 2); a spline function was retained. All dates were calibrated (Reimer et al., 2004) and are reported as ka, 1000 years before present, with a base of AD 1999, the year in which the sediment core was collected.

A total of 122 levels were sampled for chironomids, providing over 20,000 whole head capsules (HC) for analysis. Sediment samples were taken every 1 to 5cm depending on sediment availability, and were processed for chironomid analysis using standard methods (Walker, 2001). The volume of sediment sampled and HC concentrations ranged from 0.1-4cm^3 and 24-290 HC cm^{-3} (105-1683 HC dryg^{-1}), respectively. Chironomid volumetric concentrations and concentrations per gram of dry weight had very similar profiles and therefore only volumetric concentrations will be discussed. Although we attempted to obtain a minimum of 50 head capsules per sample (Heiri and Lotter, 2001; Quinlan and Smol, 2001; Larocque, 2001), this was not always possible due to either low HC concentrations or insufficient sediment availability. However, of the 122 levels retained for statistical analysis, only 3 had HC counts below 45 HC.

Head capsules were identified using taxonomic keys provided by Walker (1988; 2000); Barley et al. (2006), Heiri et al. (2004), Larocque and Rolland (2006) and Brooks et al. (2007). *Tanytarsus* spp., *Micropsectra* spp. and *Paratanytarsus* spp. were identified to the species morphotype level using Heiri et al. (2004). *Heterotrissocladius* spp. identifications to the species level were based on Larocque and Rolland (2006), and *Zalutschia* spA and spB identifications follow Barley et al. (2006). HCs were identified to the species level where possible.

Mean July air temperatures (JTemp) were estimated using the JR01 chironomid assemblages using a new collection of modern samples from across Canada and the Canadian Arctic (Fortin [4]). Although this training set contains all the lakes from the Barley et al. (2006) set, it significantly expands on Barley et al. (2006) by including a greater number of lakes from the Arctic and northern Canada (n=379). Reconstructions were also performed using Barley et al. (2006; 136 lakes) for comparison, as the two other chironomid-based paleoenvironmental reconstructions presented in this thesis (Lakes WB02, Fortin and Gajewski (2010a) [5] and KR02, Fortin and Gajewski (2010b) [6]) used this dataset for calibration. Using both calibration datasets enabled us to understand the potential impacts that training set range can have on paleoclimate reconstructions in an Arctic region.

Using both calibration datasets, a weighted average partial least squared (WAPLS; bootstrapped 1,000 times) model including three components (Fortin [4]: r^2_{boot} =0.744 and $RMSEP_{boot}$ =1.88°C; Barley et al. (2006): r^2_{boot}=0.818, $RMSEP_{boot}$ =1.46°C; both models uncorrected for spatial autocorrelation), and the modern analogue technique (MAT; retaining 5 analogues) were used. Rare taxa as identified in the respective training set studies were removed. The WAPLS models were used in this study as they were identified in the original papers as providing the most "robust" reconstructions (Barley et al., 2006; Fortin [4]). The MAT provides information regarding the geographic location of the modern analogues to the downcore fossil data.

All taxa present in the core were also present in both training sets. Squared cord distances of the closest analogues in each training set to the downcore assemblages as well as the geographical location of these analogues were examined to determine the appropriateness of each training set (Anderson et al., 1989; Birks, 1998; Gajewski et al., 2000a; Sawada et al., 2004; Viau et al., 2008). Using the Fortin ([4]) training set revealed better analogues (smaller SCDs) to the sub-fossil data and a greater number of better analogues than the Barley et al. (2006) training set.

Principal component analyses were conducted separately on the fossil diatom, pollen and chironomid taxonomical data to reveal changes in the community composition of each of these fossil groups through time. The first two axes of each respective PCA explained 28% and 9% of the changes in the chironomid community, 14% and 10% of the changes in the pollen assemblage, and 52% and 17% of the changes in the diatom community. Loadings of the most abundant taxa included in each PCA are presented in Table 2.

Results

Heterotrissocladius spp. (optimum 9.3°C, all taxa optima are from Fortin [4]) dominated the early fossil assemblage (Figures 3 and 4). As its relative abundance decreased from 7.2 to ~6.7ka, the proportion of both cold- and warm-tolerant taxa already present in the community began to increase. Taxa from the sub-tribe Tanytarsina (called here *Tanytarsina* spp. including all *Paratanytarsus* spp., *Tanytarsus* spp. and Tanytarsina-undif.; optimum

9.9°C) and from the sub-tribe Tanypodinae (Pentaneurini spp. and *Procladius* whose optima are 10.6°C and 11.1°C, respectively), became more abundant. The relative abundance and production of these thermophilic taxa remained relatively high until ~4.5ka. Colder-tolerant *Paracladius* (optimum 6.0°C) and taxa from the genus *Micropsectra* (*Micropsectra* spp. including *M. radialis*, *M. insignilobus* and *Micropsectra*-undif; optimum 7.9°C) also increased in abundance and production in the early Holocene. The relative abundance of *Paracladius* continued to increase until ~3.5ka, whereas the abundance and production of *Micropsectra* spp. were high between 6.5ka and ~5.0ka. *Sergentia* and *Psectrocladius (Psectrocladius)* (optima 8.7° and 10.6°C, respectively), were also abundant in the assemblage prior to ~4.5ka. The production of these organisms was generally highest prior to ~4.5ka. Prior to ~5.0ka, the relative abundances and concentrations of warm-tolerant chironomid taxa at Lake JR01 were generally at their highest, when compared to the rest of the core.

Beginning around 5.0-4.5ka there was a change in community composition of the chironomid, pollen and diatom communities as seen in a transition in the sample scores of the first axes of the respective principal components (Figure 5). Around this time, the thermophilic chironomid taxa from the earlier Holocene greatly decreased in relative abundance and concentrations, and cold-tolerant *Paracladius* began to dominate the assemblage (Figures 3 and 4). *Micropsectra* spp. also remained quite abundant from ~4.5 onwards (although less so between 4.5~2.5ka than in the earlier Holocene). At ~4.25ka, cold stenothermic *Abiskomyia* (optimum 6.3°C) also appeared in the assemblage and remained in high relative abundance until recent times. Although cold tolerant taxa dominate the assemblage from ~4.5ka until recent times, taxa tolerant of intermediate and warmer temperatures, such as *Zalutschia* spp. (including *Zalutschia* spA and spB types), *Corynocera* *oliveri* type, *Protanypus* and *Mesocricotopus* (optimum 10.2°C, 10.1°C, 9.2°C and 11.0°C, respectively) all become slightly more abundant than previously in the record and remained in the assemblage until the late Holocene. *Chironomus anthracinus* type (optimum 11.3°C) briefly increased at ~4.25ka, 3.4ka, and 1.6ka reaching 20%, 10%, and 10% relative abundance at those respective times. *Chironomus anthracinus* type is known to be present in greater relative abundances after disturbances (Brooks et al., 2007). After ~3.5ka, *Paracladius* dominated the assemblage and its relative abundance stabilized, although its concentration continued to increase for another 2,000 years. From ~3.4 until ~0.6ka, no major changes in relative abundances occurred other than the slight increase in relative abundance of *Micropsectra* spp. until ~1ka. At ~0.6ka *Paracladius* and *Abiskomyia* decreased in abundance and *Micropsectra* spp. and *Tanytarsina* spp. increased in relative abundances. During the last 150 years, the production of both warm- and cold-tolerant chironomid taxa increased.

Chironomid, pollen and diatom accumulation rates were calculated based on three different age depth models (Figure, 6); only trends common to all models will be interpreted. The chironomids, pollen and diatoms all show highest accumulation rates in the early Holocene, irrespective of age-depth model used. A large peak at ~5.5ka is present in all three proxies when the interpolated and spline curves are used, but is not present in the data when the age-depth data are fitted with a loess. A secondary peak is seen between 2.7 and 2.0ka. Since this is seen in all proxies and using all age depth models, this suggests that these accumulation rates are not simply an artifact of the model chosen but rather an actual representation of environmental conditions at the lake at that time. Furthermore, the broader trends present in the proxies' accumulation rate profiles are largely coherent with those present in these proxies' respective concentrations profiles.

Sediment organic and biogenic silica contents were highest prior to ~5.0ka (Figure 5). Similarly, the concentrations of diatom and pollen fossils reached their highest values prior to ~4ka. Chironomid concentrations showed no significant long-term trend, although values were slightly higher prior to ~5.0ka (Figure 5). Overall aquatic and terrestrial production, as measured by sediment organic and biogenic silica content as well as pollen and diatom concentrations and accumulation rates, then decreased from ~5.0 to ~4.0ka, and remained lower from 4.0ka to the most recent times than prior to 4.0ka (Figures 5 and 6). At ~1.2ka pollen, diatom and chironomid concentrations began to increase, only to decrease again from 0.6ka to 0.15ka, with an abrupt peak at 0.4ka. From ~0.15ka to the recent, concentrations and accumulation rates of all fossil organisms and sediment BSi content increased (Figures 5 and 6). This represents an increase in overall lacustrine production over the last 150 years.

Mean July air temperatures inferred from the fossil chironomid assemblages based on the WAPLS and using the modern calibration dataset of Fortin ([4]) can be grouped into three periods: 7.2ka to 5.5ka, 5.5ka to ~1.ka and ~1ka to recent times (Figure 7). The early Holocene at Lake JR01, prior to 5.5ka, is characterized by warm temperatures. The temperatures experienced during this phase were warmer than at any other time at this lake, reaching up to 7.4°C at 6.8ka. Temperatures generally cooled from 6.7ka to 5.5ka, with an abrupt peak in temperatures at 5.7ka. From 5.5ka to ~1ka, inferred mean July air temperatures remained relatively stable (around ~6.3°C). Starting at ~1ka, inferred temperatures slowly decreased until recent times. Superimposed on this cooling trend were further dips in temperature from 0.7ka to 0.5ka, and 0.4 to 0.15ka, the former "dip" being the colder of the two. The sampling resolution during this period is such that the decreases and increases in temperature are generated by more than just one sample each. After the last brief warming period that culminated at 0.15ka, temperatures decreased to recent times reaching temperatures as cool as 4.5°C. Using the MAT with this dataset showed no long-term trend in reconstructed mean July air temperatures.

The Barley et al. (2006) calibration equation was also used to generate a mean July air temperature reconstruction for Lake JR01 (Figure 7) in order to facilitate comparison between this reconstruction and those presented in the other chapters in this thesis, and to illustrate the differences in reconstructions that are obtained using different calibration data. Although both the WAPLS reconstruction based on Fortin ([4]) and that based on Barley et al. (2006) showed a long-term cooling, there are some differences between them. For example, the reconstructions based on the Barley et al. (2006) training set predicted higher temperatures throughout the entire Holocene than those inferred using Fortin ([4]). Using Fortin ([4]) shows relatively stable temperatures between 5.5ka and 1.0ka, whereas using Barley et al. (2006) a cooling is reconstructed during this time. The absolute values differ between the reconstructions as well. However, what is most striking are the similarities between the two reconstructions regarding the large- and small-scale temperature variations from 1ka to recent times. The Barley et al. (2006) MAT mean July air temperature reconstruction infers warmest temperatures occurring prior to 5.5ka, followed by constant temperatures until ~2.2ka and then progressive cooling to recent times.

Discussion

Chironomid communities and production

Chironomid taxa present at Lake JR01 over the past 7,200 years are typical of those found in modern-day cold, oligotrophic lakes. The Holocene chironomid community composition at Lake JR01 is similar to that present in the sediment records from lakes on Baffin Island (Fog and Brother of Fog Lake, Francis et al., 2006; CF3, Briner et al., 2006; CF8, Axford et al., 2009a), Southampton Island (Lake 4 and Caribou, Rolland et al., 2008; 2009), on Victoria Island (WB02 and KR02; Fortin and Gajewski, 2010a [5]; 2010b [6]) and for the last 2ka in lake V57 also from Victoria Island (Porinchu et al., 2009b). Although the overall fauna is the same, the relative abundances of these taxa differ between lakes.

Overall chironomid production during the Holocene is much higher at Lake JR01 than at other Arctic lakes, and even at lakes whose inferred temperatures over the Holocene are greater than those for Lake JR01. Pollen concentrations and sediment organic content over the Holocene at Lake JR01 are also considered quite high for an Arctic lake (Zabenskie and Gajewski et al., 2007). The higher production at this lake may be due in part to its more southerly location but may also be the result of local-scale environmental influences on this lake, such as bedrock composition and watershed properties.

Holocene climate change in the Boothia Peninsula

The sediment analysis at Lake JR01 revealed that an important transition occurred at ~5.5 ka. Prior to 5.5ka, aquatic and terrestrial production were high and chironomid-inferred mean July air temperatures were warmer than in the mid- to late-Holocene. Temperatures cooled or remained stable from ~5.5-1.0 ka, during which time ecosystem production was lower than during the early Holocene. Based on the changes in diatom species diversity at ~5.0ka, which is reflected in the PCA scores, a cool period starting at this time was also inferred by Leblanc et al. (2006), although the magnitude of the change was not estimated using the diatom assemblages due to lack of appropriate modern data. The pollen-based mean July air temperature reconstruction does not show the same warming in the early Holocene as inferred from the chironomid and diatom assemblages; however it does support the hypothesis that more stable environmental conditions existed through the mid-Holocene until ~1ka. Zabenskie and Gajewski (2007) found a slight warming between 3.5 and 2.5ka, although this is based on only two samples in a portion of the core where few samples were available. Temperatures then began to cool at ~1.0ka; this cooling lasted until recent times. Evidence of the Little Ice Age is present in Lake JR01's chironomid, pollen and diatom records. There is no indication of a recent (last 150 years) warming in the chironomid based temperature reconstructions, although overall aquatic and terrestrial production did increase as did the pollen-based temperatures in the most recent sediments. Recent inferred temperatures remain cooler than those inferred for the earlier Holocene using both pollen and chironomid records, up to 3°C cooler based on the chironomid assemblages.

Importance of modern data in paleoclimate reconstructions

Analysis of the spatial distribution of the analogues provides insight into the reasons a particular reconstruction is obtained as well as identifying potential problems with the reconstructions (e.g., Gajewski et al., 2000a; Viau et al., 2008). Using the Fortin ([4]) modern training set and based on the results of the MAT, the difference in temperatures between the top 5 analogues (i.e. the range) for each downcore level prior to 4.6ka is far greater than at other times in the core; on average 4.1°C± 2.6°C prior to 4.6ka compared to 2.6°C±1.0°C post 4.6ka. This is because most of the levels from the early Holocene select within their five best modern analogues some of the warmer lakes located as far south as central Northwest Territories (65° lat), but also several of the "colder" lakes located on Ellesmere Island (76° lat). In the original training set, Fortin ([4]) used the New et al. (2002) gridded data set to extract lake mean July air temperatures. Fortin ([4]) also shows, however, that using the New et al. (2002) temperatures leads to some significant underestimation of temperatures for most of these lakes on Ellesmere Island. In reality, these northern lakes have mean July air temperatures and vegetation closer to those found in the lower warmer Arctic (Garneau and Alt, 2000; Atkinson and Gajewski, 2002). The mesoclimate of the region is not sufficiently estimated by the New et al. (2002) global gridded dataset used to assign temperature data to the sites. Thus, the analysis of the location of the analogues and of the chironomid community suggests that temperatures prior to 4.6ka were in fact warmer than predicted by the MAT and even by the WAPLS model. Prior to 4.6ka, more southerly lakes, as well as those from the "oasis" of the Fosheim, are analogues for the chironomid community at Lake JR01. After 4.6ka, the best five analogues for the chironomid communities downcore are almost all located between 68°d.d. and 72°d.d latitude in the colder regions of the Arctic, where the actual temperatures are better estimated by the gridded dataset, and with only a few cases where an analogue is found on Ellesmere. This underestimation of the temperatures in the modern set could likely more directly affect the reconstructions using the MAT than those using WAPLS and explains in part the differences in inferred temperatures generated by different models for the early Holocene (Fortin [4]).

When using Barley et al. (2006) as the calibration dataset, the model predicted 1) overall warmer mean July air temperatures than when using Fortin ([4]), and 2) a greater magnitude of cooling through time. The difference in temperature between the two training sets' reconstructions was greater in the early Holocene and decreased through time (difference of ~2.5°C and ~1°C in the early and late Holocene, respectively). The SCD between analogue and fossil samples were larger using the Barley et al. (2006) training set, suggesting that this dataset is less appropriate than using the Fortin ([4]) set. For both training sets, the closest modern analogues to the downcore fossil assemblages were those found in the Arctic regions. Barley et al. (2006), however, retained only very few Arctic (i.e., colder) sites due to decisions about removing samples with relatively low minimum counts; as a result, analogues to the downcore assemblages were found to the south and the calibration model reconstructed warmer temperatures. In fact, the best analogues in the Barley et al. (2006) training set for samples older than 4.3ka are virtually never among the top five best analogues from the Fortin ([4]) data for the fossil samples for that same period. The main failing of the Barley et al. (2006) training set in reconstructing past temperatures for this and other Arctic sites is not that it does not contain lakes far enough north, but rather that it did not contain enough lakes from these colder regions—thus underestimating the cold end of each taxa's tolerances as well as providing poor analogues for the downcore data. This type of argument also holds true for the larger Fortin ([4]) training set, which would undoubtedly be greatly improved by increasing the density of sites it contains. Thus, it is important to further expand the modern chironomid data to not only cover a greater range for each environmental variable but also to obtain a greater density of sites from every region. Chironomid researchers need a public dataset spanning the entire continent to ensure that analogues can be found in downcore studies—similar to what has been achieved by palynologists in the establishment of the North American Modern Pollen database (Whitmore et al., 2005).

Holocene climatic changes in the Canadian Arctic

The general trends of the chironomid inferred mean July air temperatures at Lake JR01 are similar to those of many other chironomid- and other proxy-based records from across the Arctic. A warmer, more productive early Holocene was also inferred on Western and Northern Victoria Island (Lakes KR02 and WB02, Podritske and Gajewski, 2007; Peros and Gajewski, 2008; Fortin and Gajewski, 2010a [5]; 2010b [6]) using primary production indices as well as pollen, chironomid and diatom records. Records from Baffin Island confirm the presence of a warmer period during the early Holocene (Briner et al., 2006, Francis et al., 2006, Axford et al., 2009a), as does the Kaufmann et al. (2004) study, which infers the Holocene Thermal Maximum as having occurred in the western Arctic between 8.9 ± 2.1 ka and 5.9 ± 2.6 ka. Ice melt percent was also highest during this time, as recorded by the Agassiz Ice Core on Ellesmere Island (Fisher et al., 1995)

A cool period occurring at Lake JR01 through the middle Holocene is also interpreted from lake sediment cores on Victoria Island, northern Boothia Peninsula, Somerset Island, Prince of Wales Island and Baffin Island (Gajewski, 1995; LeBlanc et al., 2004; Briner et al., 2006, Francis et al., 2006; Finkelstein and Gajewski, 2007b; Zabenskie and Gajewski, 2007; Axford et al., 2009a; Fortin and Gajewski, 2010a [5]; 2010b [6]).

At Lake JR01, inferred temperatures begin to cool further from ~1ka based on both the chironomid and pollen records, which may correspond to the Little Ice Age. This cooling was regionally observed at approximately the same time in the chironomid-based records from Southampton Island (between 0.6 and 0.3 ka, Rolland et al., 2008) and southern Victoria Island (between 0.9 and 0.3 ka, Porinchu et al., 2009b), and in the diatom records (Wolfe, 2003; LeBlanc et al., 2004) and pollen records (Finkelstein and Gajewski, 2007b) from across the Arctic.

A recent warming of the past few decades, observed at sites across the Arctic (and summarized in Kaufman et al., 2009) is present in the pollen-inferred temperature records at Lake JR01 but not in the chironomid based temperature record, although sediment production proxies as well as fossil concentrations at this lake do increase over the last 150 years. Temperatures inferred for the past 150 years at Lake JR01 are cooler than those inferred for the early Holocene, up to 3°C cooler based on the chironomid record. A number of other studies from across the Arctic, such as on Victoria, Southampton and Baffin Islands, have found that inferred modern temperatures were equivalent or cooler than those inferred for the early Holocene (Briner et al., 2006; Francis et al., 2006; Rolland et al., 2008; Axford et al., 2009a; Fortin and Gajewski, 2010a [5]; 2010b [6]).

Ecosystem Changes during Holocene climate changes

The largest change in trophic status at Lake JR01 appears to have occurred around 5.0ka, a time when the aquatic and surrounding terrestrial ecosystems became less productive and when inference models predict the stabilizing of temperatures after 2 millennia of cooling (Figure 5). At the start of this transition at ~5.3ka, chironomid production increased quite significantly for a brief period, with the concentration of both warm and cold chironomid taxa increasing. This peak is only constrained by two samples, although it is worth noting that a similar phenomenon is also seen at a number of lakes across the Arctic (Figure 8). At many of the sites for which Holocene chironomid records are available, a peak in chironomid concentration, which is also only identified by one or two samples, is observed at the onset of environmental changes (Figure 8; Briner et al., 2006; Francis et al., 2006; Axford et al., 2009a; Fortin and Gajewski, 2010b [6]; this study). This increase in production may be the chironomid community's response to large changes occurring in the lake's environment at that time. For example, at Lake KR02 on western Victoria Island (Fortin and Gajewski, 2010b [6]), a peak in chironomid production occurred at 6.9ka and 1.6ka, which corresponded to the onset of periods of climatic and environmental change (Figure 8). Furthermore, during this time at Lake KR02, both cold- and warm-tolerant taxa increased in abundance and concentrations. At Lake CF8, (Baffin Island, Axford et al., 2009a), chironomid concentrations are highest as inferred temperatures rapidly increase at ~10.5ka and are high again at ~7.5ka as inferred temperatures cool. Similarly, at Lake CF3 (Baffin Island, Briner et al., 2006), chironomid concentrations peak at ~10ka at the start of a rapid increase in inferred temperatures. At these sites, chironomid concentrations spike at the onset of large changes in temperatures, both when temperatures are warming and cooling. High overall chironomid production at environmental transitions as seen in the chironomid-based inferred temperature record, is also observed at Fog Lake on Baffin Island at depths of 115cm, 82cm and 53cm which are depths that are identified based on a number of proxies in the sediment as major transitions (zone boundaries) in the environment (Francis et al., 2006). These increases in chironomid concentrations are always short in duration and in most of these cases are only represented by two or fewer samples. However, this response at five sites suggests that high resolution analyses at times of environmental change may provide insight into ecosystem response to environmental change. Finkelstein and Gajewski (2007b) also report increased diatom diversity at Lake PW03 on Prescott Island, Nunavut at times of climatic changes, and they suggested this could be explained by the intermediate disturbance hypothesis. The intermediate disturbance hypothesis suggests that unstable environments, due to a reduction in competitive exclusion, lead to higher species diversity (Connell, 1978). We hypothesize that the increase in diversity of both cold and warm taxa may also lead to a more productive non-equilibrium community at times of climatic change. It remains unclear if these findings are applicable outside of the Arctic. Nonetheless, these finding further highlight the complexity of the relationship existing between chironomid community (production and composition) and environmental change. It also indicates that modern chironomid communities may be in a state of disequilibrium due to present climatic changes and this may need to be considered when using these modern assemblages to infer past conditions.

Conclusion

At Lake JR01 from Boothia Peninsula, Nunavut, chironomid-inferred mean July air temperatures were warmest in the early Holocene reaching as high as 7.5°C. Temperatures decreased between 7.2ka until 5.0ka. Overall terrestrial and aquatic production, as indicated by chironomid, pollen and diatom concentrations and accumulation rates, as well as sediment organic and biogenic content, were higher prior to 5.5ka than at any other time in the Holocene. The diatom community assemblages during the early Holocene also indicate that this was a warm period in the lake's history. Between 5.0-1.0ka, the lake was cooler and less productive. Inferred temperatures, based on both the chironomid and the pollen records, indicate a cooling starting at 1.0ka that corresponds to the Little Ice Age (LIA). Interpretation of changes in the diatom assemblages starting at 1.0ka offer further evidence of a cooling at this time. The pollen-based temperature record indicates warming from 0.10ka to recent times which is not present in the chironomid-based temperature reconstruction. Indices of biological production of both aquatic and terrestrial environments do increase in the last 150 years. Modern inferred temperatures based on both pollen and chironomids are cooler than those inferred for the early Holocene, up to 3°C cooler based on the chironomid record. The overall climatic trends recorded by both the pollen and chironomids at Lake JR01 are comparable to those observed at other sites across the Arctic, offering further evidence that regional-scale climates have influenced Arctic aquatic and terrestrial ecosystems over the Holocene.

A new northern North American chironomid calibration dataset of modern sediment samples (Fortin[4]) was used to infer past mean July air temperatures at Lake JR01, and the results compared to those derived from a previously published set (Barley et al., 2006). The inclusion of more samples and, in particular, more samples from the Arctic Islands provided more good modern analogues to the core data. Some issues still remain in reconstructing past climates in Arctic North America, and methods for identifying potential problems are discussed in this study.

Brief periods of greater chironomid production of both warm- and cold-tolerant taxa occurred at Lake JR01 at the onset of periods of climatic and environmental change. Elevated overall chironomid production is also seen during environmental transitions in the Holocene record of other lakes from across the Arctic. A temporary increase in production may be a consequence of the chironomid community adjustment during environmental transitions.

Table 1 Radiocarbon dates for Lake JR01 sediment core. All analysis conducted by Beta Analytical Inc., Miami Florida. Dates were calibrated using Calib 5.01 (Reimer et al., 2004) and converted to years ka BP, with 1999, the year of collection, as base

Beta analytical reference	Depth (cm)	^{14}C yr BP	Mean calibrated calendar years BP (1999)	
			years BP	years ka BP
156532 [a]	30-35	1290±40	1244	1 244
204646 [b]	59-61	2120±40	2195	2 195
156533 [b]	95-100	2410±40	2571	2 571
204647 [a]	153-154	3030±40	3268	3 268
156534 [b]	220-225	4290±40	4899	4 899
156535 [b]	295-300	4890±40	5700	5 700
210910 [a]	349-350	4990±40	5795	5 795
204648 [a]	395-396	5000±40	5807	5 807
204649 [a]	453-456	6160±40	7106	7 106
156536 [b]	544-549	6320±40	7335	7 335

Material dated were [a] bryophytes, leaves and branch fragments or [b] plant material and chironomids.

Table 2 Loadings of the dominant taxa on the first and second axis of a principal component analysis of the a) chironomid, b) pollen and c) diatom fossil record at Lake JR01

a.

Chironomid	AXIS 1	AXIS 2
Abiskomyia	-1.73	0.23
Protanypus	-1.58	-0.33
Tanytarsus spp	1.46	0.67
Procladius	1.43	-0.61
Pseudodiamesa	-1.38	1.67
Paracladius	-1.37	-1.34
Heterotrissocladius spp	1.29	-1.19
Mesocricotopus	-1.26	-1.46
Zalutschia spB	-1.25	-1.39
Parakiefferiella nigra-type	-1.25	-0.81
Paratanytarsus spp	1.20	-0.16
Psectrocladius Psectrocladius	1.05	-0.71
Pentaneurini spp	1.00	-0.94
Corynocera ambigua type	0.92	0.34
Tanyarsina-other	0.84	1.46
Eukiefferiella/Tvetenia spp	-0.80	0.23
Sergentia	0.66	-0.61
Micropsectra spp	-0.55	2.39
Corynoneura arctica-type	-0.47	0.66
Cricotopus/Orthocladius spp	-0.40	-0.26
Zalutschia sp A	-0.35	-0.30
Limnophyes	-0.29	0.78
Hydrobaenus/Oliveridia spp	-0.26	0.11
Stictochironomus	0.17	-1.61
Corynocera oliveri-type	-0.13	1.12
Chironomus anthracinus-type	0.08	-0.52
Metriocnemus spp	0.06	-0.45

b.

Pollen	AXIS 1	AXIS 2
Cyperaceae	2 21	-0 06
Ericaceae	-1 67	-0 70
Oppositifolia	-1 66	0 44
Brassicaceae	-1 45	-0 40
Polygonum viviparum	1 44	-0 89
Caryophyllaceae	-1 44	-0 61
Salix	1 25	-1 09
Saxifragaceae	1 09	-1 60
Chenopodiaceae	0 76	1 17
Oxyria	0 62	-0 64
Asteraceae	0 57	1 73
Potentilla	0 46	0 92
Dryas	0 45	-0 13
Poaceae	0 45	-0 79
Rosaceae undifferentiated	-0 43	-1 98
Ambrosia	-0 36	-0 13
Fabaceae	-0 36	-1 14
Ranunculaceae	0 34	-0 26
Rubus chamaemorus	-0 26	1 18
Artemisia	0 23	0 12
Papaver	-0 10	-1 80
Plantago maj	0 00	-0 18

c.

Diatom		
Achnanthes rosenstockii	1 34	0 03
Achnanthidium minutissimum spp	1 30	0 25
Staurosirella pinnata var pinnata	-1 26	-0 25
Pseudostaurosira pseudoconstruens	1 26	-0 07
Staurosira construens var venter	-1 11	0 40
Staurosira aff Elliptica *	1 04	-0 25
Pseudostaurosira brevistriata	0 97	0 44
Staurosira construens form 2	-0 78	1 38
Staurosira construens form 1	0 53	1 61
Staurosirella pinnata var acuminata	0 47	1 71
Amphora ovalis var pediculus	0 02	1 74

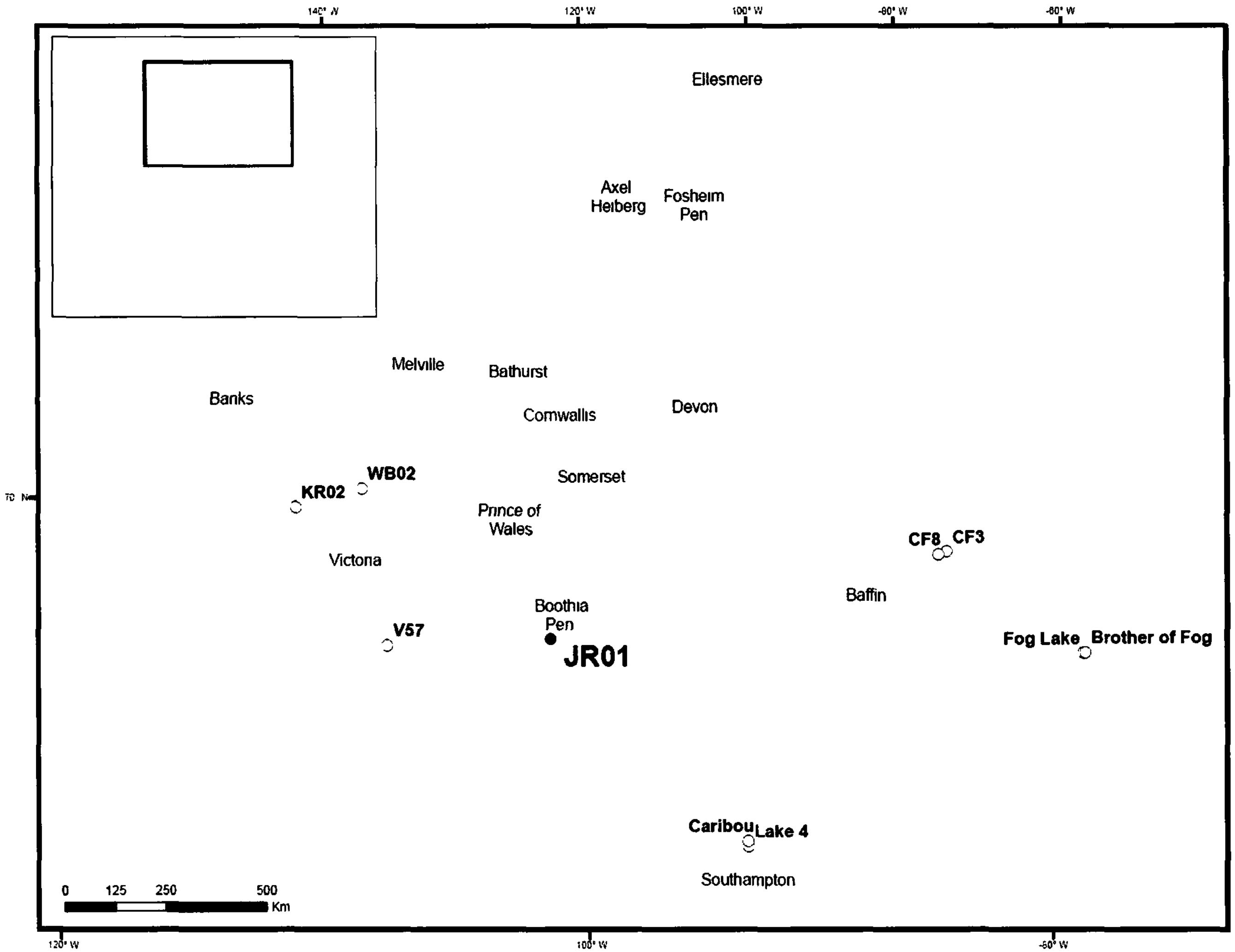

Figure 1 Location of study area, Lake JR01, in the Canadian Arctic. All other studies referenced in the text are also shown (see text for references)

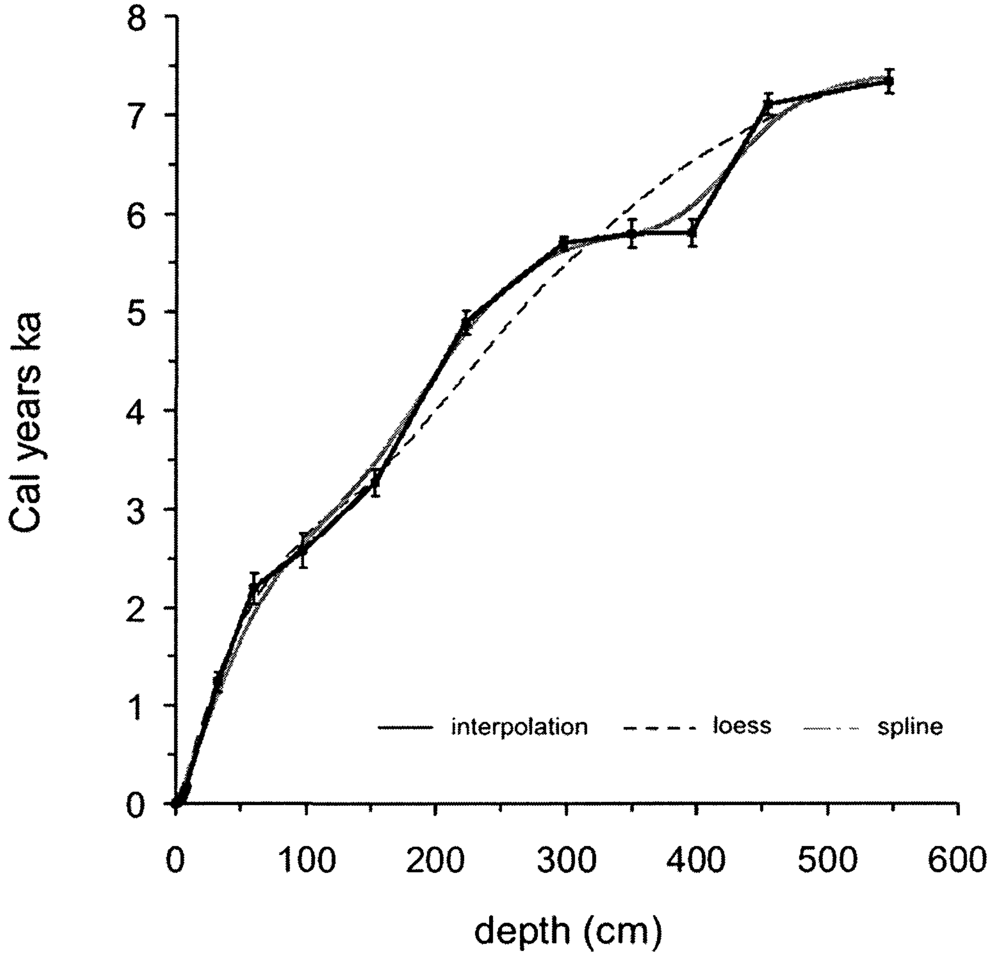

Figure 2 Sediment chronology at Lake JR01. The black solid line represents an age-depth profile generated by interpolating between the 10 calibrated ^{14}C and 8 ^{210}Pb dates. The dotted line is a loess smoothing and the grey line a spline function applied to these dates. Age in calendar years ka, 1000 years before 1999 which is the year the core was collected

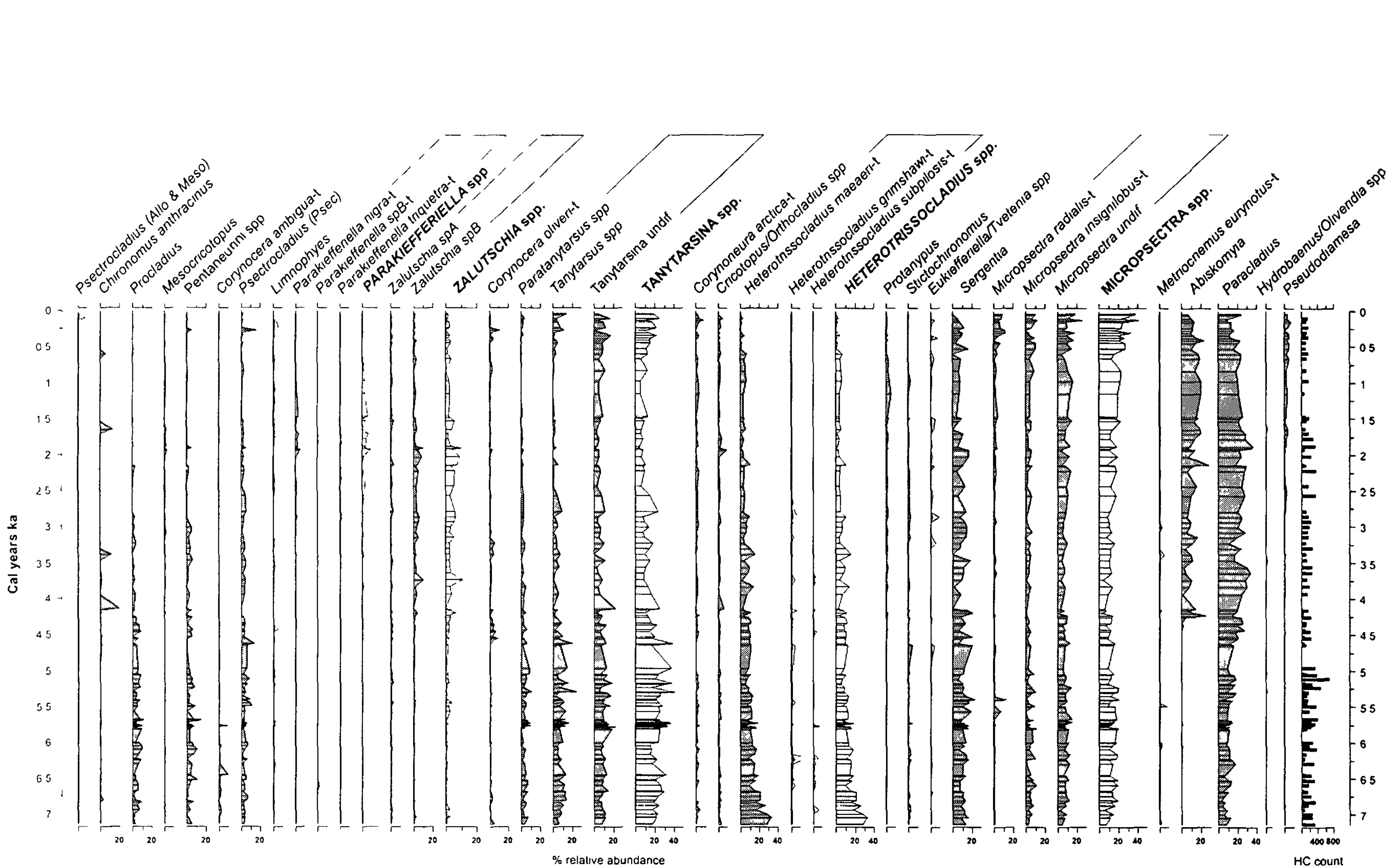

Figure 3 Percent relative abundances of all chironomid taxa at Lake JR01. Taxa are plotted in order of decreasing optimal mean July air temperature (°C) (Fortin [4]). Taxa that were subsequently combined for the mean July air temperature reconstruction are grouped together with a bracket. The non-shaded profiles with taxa label in bold and in all capitals represent the sum of the relative abundances of the taxa in the bracket to the left. *Paratanytarsus* spp. includes both *P.austriacus*, *P. penicillatus* and *P.* undifferentiated and *Tanytarsus spp.* includes *T. lugens*, *T. mendax* and *T* undifferentiated. The "–t" denotes "type". Head capsule (HC) count sums for each level are presented on the far right of the graph. Exaggeration lines were added to the profiles of the less abundant taxa

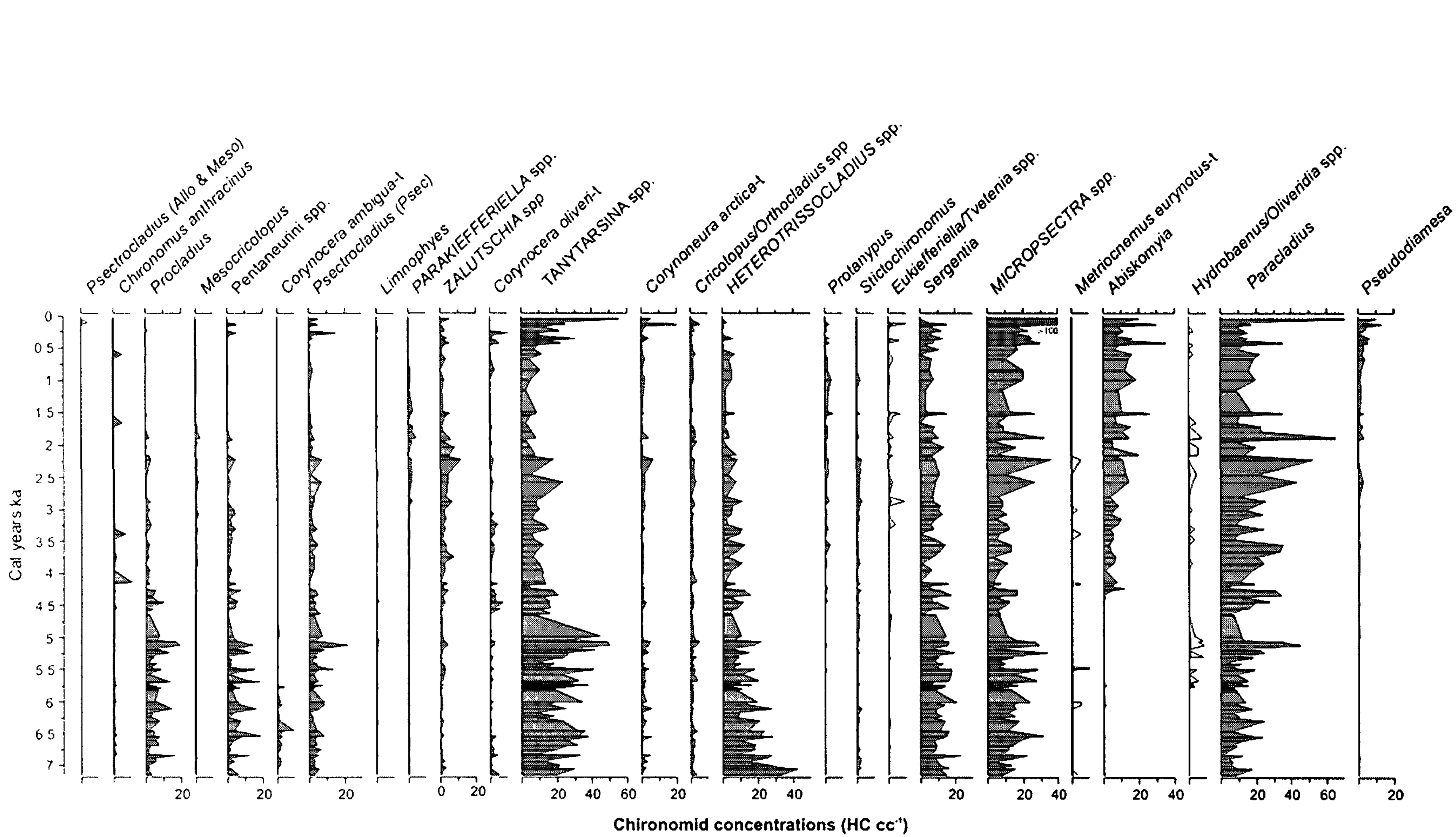

Figure 4 Chironomid concentrations of select chironomid taxa from Lake JR01 during the past 7,200 years. Taxa are in order of decreasing optimal mean July air temperature (°C) (Fortin [4]). The "–t" denotes "type"; exaggeration lines were added to the profiles of the less abundant taxa

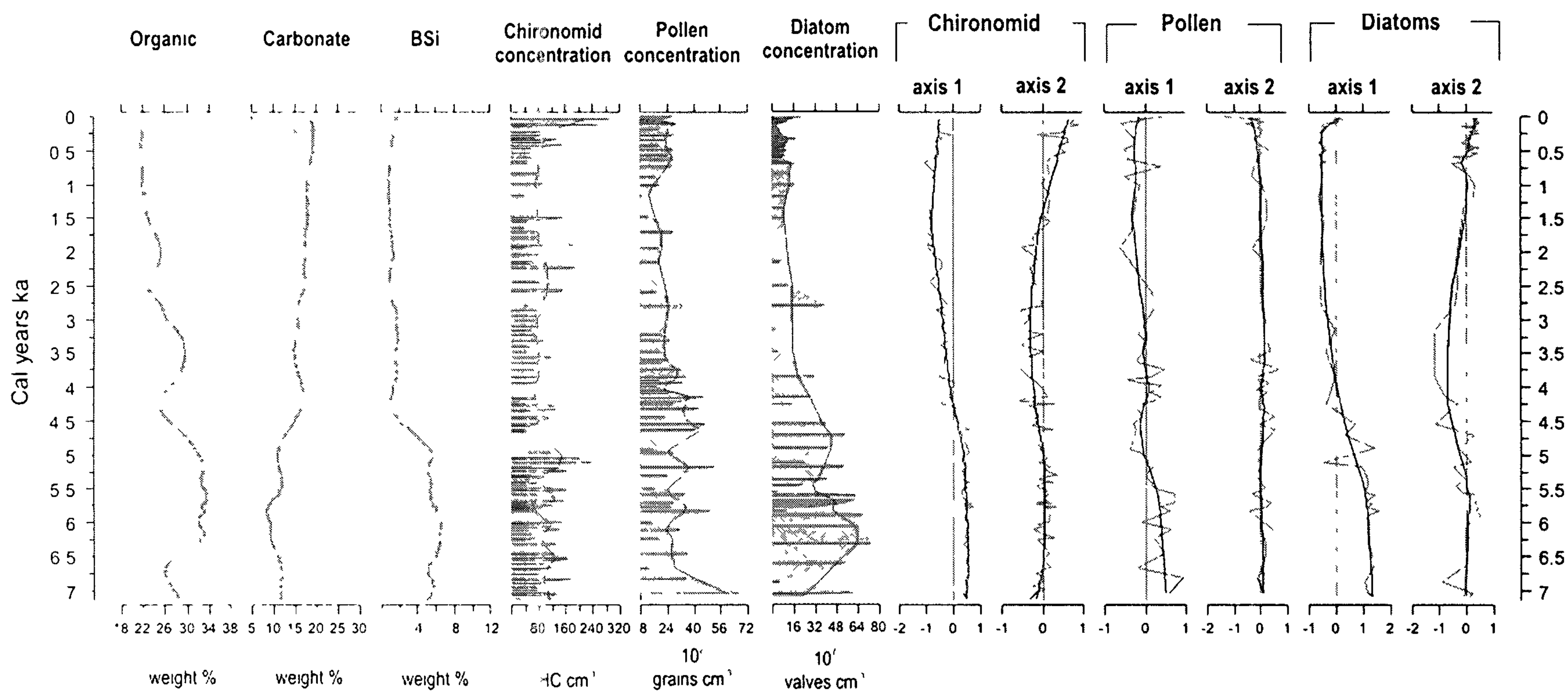

Figure 5 Sediment organic, carbonate and biogenic silica content (%) and chironomid head capsule (HC), pollen grain and diatom valve concentrations at Lake JR01 during the last 7,200 years. The sample scores for the first and second axis of the respective chironomid, pollen and diatom principal components analysis are plotted on the right. The thick black line on all plots is a loess smoother of the data.

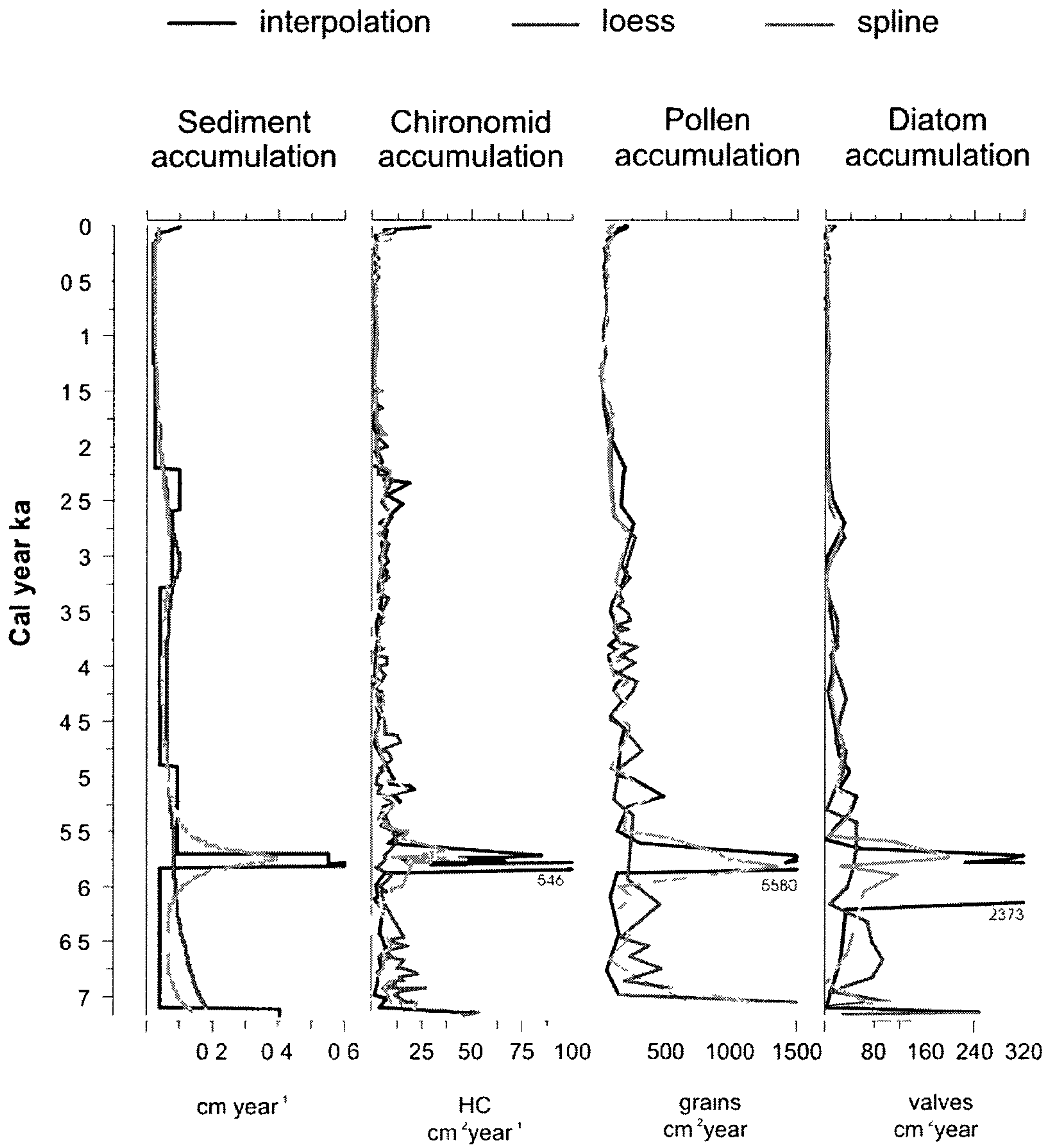

Figure 6 Chironomid HC, pollen grain and diatom valve accumulation rates at Lake JR01 using three different age depth models: interpolation between ^{210}Pb and ^{14}C dates (black line), a loess smoother (dark grey line) and a spline function (light grey line)

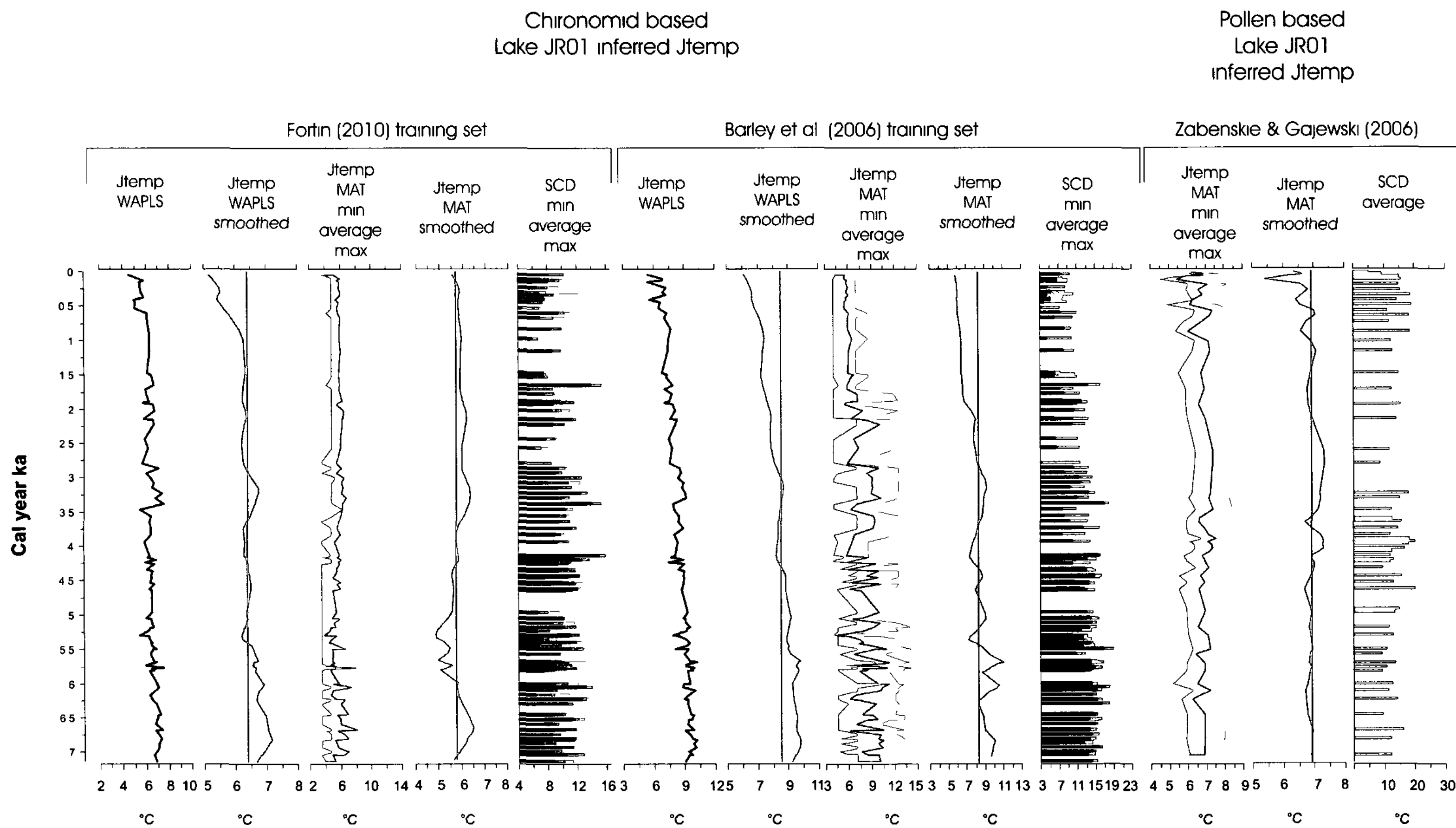

Figure 7 Chironomid inferred mean July air temperature (JTemp) at Lake JR01 over the last 7,200 years using both WAPLS and the Modern Analogue Technique (MAT) using two calibration datasets - Fortin ([4]) and Barley et al. (2006). Pollen-based JTemp reconstruction from Zabenskie and Gajewski (2006). A loess smoother was used to generate all smoothed curves. Error bars are presented for the chironomid inferred temperatures (horizontal grey lines). JTemp MAT profiles show for each downcore level the temperature of the coldest of the 5 best modern analogue (dark grey), the average temperature of the 5 best analogues (black line) and the temperature of the warmest of the 5 best modern analogues (light grey), as measured by squared chord distance (SCD)

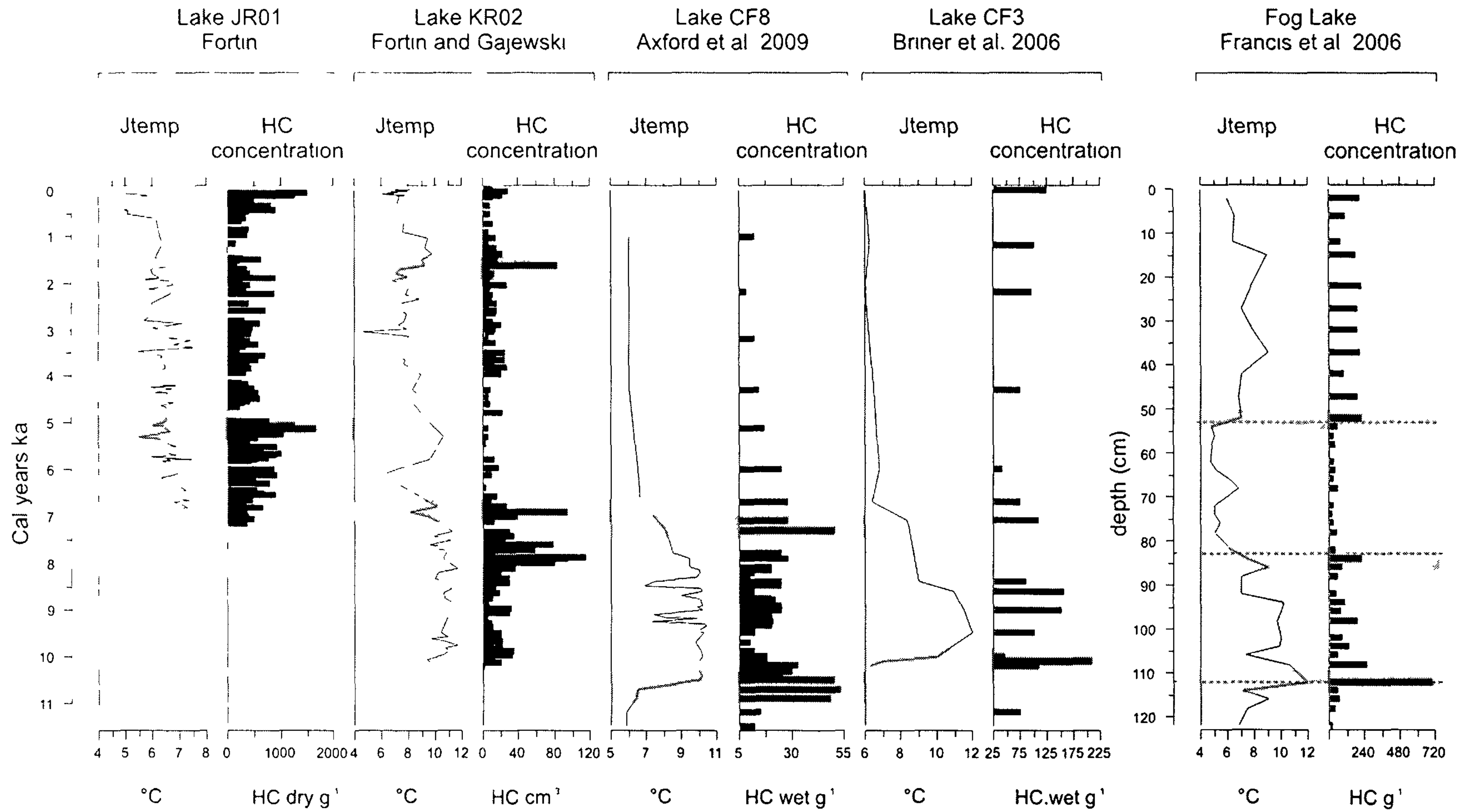

Figure 8 Mean July air temperature (JTemp) and chironomid concentration profiles for Lake JR01 (Boothia Peninsula, Nunavut; this study), Lake KR02 (Western Victoria Island, NWT, Fortin and Gajewski, 2010b [6]), Lake CF8 (Baffin Island; Axford et al., 2009a), Lake CF3 (Baffin Island; Briner et al., 2006) and Fog Lake (Baffin Island; Francis et al., 2006). Fog Lake profiles are plotted according to depth and the dotted lines separate zones according to the original study. This core is though to contain the past 52ka. Grey bands on all profiles represent JTemp transition zones which correspond to increased chironomid production

Chapter 8: Conclusion

The purpose of this thesis was to investigate long-term climatic variations and their impacts on aquatic ecosystem functioning in the Canadian Arctic using a paleolimnological approach. This was done in three Holocene cores from the Canadian Arctic, and these are the first studies from the central and eastern Arctic to use chironomid fossils to reconstruct past climates of the region. As a first step in a paleolimnological study, the modern relationship between the fossil organism or sediment parameters and environmental factors must be quantified. Modern samples from across the Arctic were collected and analyzed to quantify the relation between primary production indices, chironomid assemblages and environmental parameters.

In Chapter 2, this thesis first examined the relationships among lacustrine sediment organic, carbonate and biogenic silica content and lake environmental conditions across the Canadian Arctic. We generated a model for predicting lake water pH using these measures, providing a new quantitative tool for deriving past environmental conditions in the Arctic from lacustrine sediment cores. This is particularly useful, as the measures of these sediment parameters are relatively easy to obtain, compared to microfossil data. Thus, this tool provides an opportunity to develop high temporal resolution pH histories of Arctic lakes. It was determined that bedrock composition, which affects the elemental composition of the lake water, was the main environmental factor affecting sediment organic, carbonate and biogenic silica content. Air temperature was also significantly related to sediment biogenic silica and organic content, and in the context of paleolimnological studies where bedrock composition remains relatively constant through time, it may be possible to reconstruct temperature variations through time using these parameters. The relationship between these parameters can be used in lake sediment cores to quantify past environmental changes in these lakes.

Several studies had presented modern chironomid data from various regions of the Canadian Arctic and Alaska, and these results are used to interpret fossil assemblages from sediment cores as well as describe the distribution of these organisms through the Arctic. Some of these studies presented inference models for estimating past July air temperatures using chironomid data. However, preliminary work suggested that there were too few data from the High and Middle-Arctic regions incorporated in these training sets to make them appropriate for use in reconstructing past conditions at these higher latitudes. As such, chironomids were extracted from the sediments of a series of Arctic lakes, and these were analyzed in relation to measures of the physical and chemical environment (Chapter 3). This study also provided an opportunity to explore some methodological issues that had rendered comparisons between previous studies difficult. Using 88 lakes from across the Canadian Arctic Archipelago, including 41 new samples analyzed for this study, it was determined that mean July air temperature, lake morphometry and carbon content of the sediment and lake water influenced chironomid distribution. The importance of using accurate environmental data was illustrated through an analysis of the temperature data typically used by paleolimnologists as input to these inference models. Using a global gridded temperature dataset as the source of climate data for development of a transfer function introduces some errors when reconstructing past conditions in a data-poor and topographically complex area such as the Arctic. Practically, there is no alternative, so these datasets will continue to be used, however, their limitations must be considered when interpreting quantitative paleoclimate reconstructions. In another sensitivity analysis, rare taxa were excluded using several commonly used criteria. Since it is difficult to estimate statistical parameters with few instances of occurrence, rare taxa are commonly excluded from analyses, although there is no universally accepted criterion for exclusion. It was found that the exclusion criteria selected made little difference in the multivariate analyses conducted. While a model for inferring past mean July air temperature was derived from this training set, we concluded that this Arctic transfer function may be of limited use due to the narrow ranges of the environmental gradients it covers. The chironomid and environmental data for Arctic lakes must, however, be included in paleoenvironmental studies, as they provide potentially better modern analogues to the downcore fossil data for lakes located in colder regions.

The chironomid and environmental data from Chapter 3 were combined with those from four previously published studies to create a large dataset of 379 lakes from northern North America, including sites from Alaska to northern Québec and from south of treeline to Ellesmere Island (Chapter 4). An inference model for estimating mean July air temperature from chironomid assemblages in sediment cores was developed. This dataset spanned a much larger mean July air temperature gradient than each of the already existing training sets. It also included a much greater diversity of chironomid species assemblages, thus improving the likelihood that a modern analogue to the downcore fossil data will be found in the training set for a large variety of lakes. Again, we found that lake morphometry, carbon content and air temperature are all correlated with chironomid distribution. This inference model was not available when the paleolimnological studies of Lakes WB02 (Chapter 5) and Lake KR02 (Chapter 6) were completed, but it will be used with the data from these two lakes as well as the data from Lake JR01 (Chapter 7), as will be described below, to provide improved air temperature estimates during the Holocene across the central and western Arctic (Figure 1 and 2).

The Holocene environmental history for the Canadian Arctic was assessed at three lakes from Northern Victoria Island (Lake WB02, Chapter 5), Western Victoria Island (KR02, Chapter 6) and Boothia Peninsula (JR01, Chapter 7) using high temporal-resolution analyses of the chironomids and sediment parameters preserved in the sediment cores. At Lake WB02 (Chapter 5), chironomid production as well as organic and biogenic production were highest prior to 5.5ka, low throughout the mid- to late Holocene and increased rapidly over the last 150 years. The chironomid assemblages throughout the Holocene were dominated by cold-tolerant *Paracladius* and *Heterotrissocladius maeaeri*–type chironomid taxa. This high-Arctic lake generally had very low overall production, with low values of sediment organic, biogenic silica content and chironomid production through time. It was qualitatively inferred from the sediment record that conditions were warmest in the early Holocene. This period was followed by a cooling which was interrupted by a recent warming. The inference model initially used to qualitatively reconstruct past mean July air temperatures (Barley et al., 2006) proved inappropriate for this cold northern lake. Based on this inference model, mean July air temperatures at Lake WB02 remained relatively constant until 1.0ka, at which time they decreased and then increased again at 0.25ka. However, due to the lack of good modern analogues to the downcore fossil data in the training set, we determined that this temperature reconstruction was less reliable than may be desired. Below, I will show a new chironomid inferred mean July air temperature profile for Lake WB02, which was generated using the transfer function developed in Chapter 4. This new temperature profile, as it is different from the original one, better supports the general conclusions made, based on the other proxies in the core, regarding the environmental history at Lake WB02.

Holocene climatic changes were also evaluated at Lake KR02 (Chapter 6). The chironomid assemblages through the Holocene were comprised of a greater relative abundance of relatively warmer-tolerant taxa, such as taxa from the genus *Micropsectra*, than those of the polar desert Lake WB02. The Barley et al. (2006) training set was once again used to reconstruct past July air temperatures, but in this case the training set contained a larger number of acceptable analogues to the past fossil assemblages at this lake, and therefore generated more robust inferred past temperatures. The early Holocene at Lake KR02, prior to 6.5 ka, was characterized by high overall chironomid and primary terrestrial and aquatic production resulting from the warmer inferred summer air temperatures. As temperatures decreased in the mid- to late- Holocene, so too did overall production. A further decrease in temperatures and production occurred at 1.0ka. Inferred temperatures increased from ~0.15ka but remained variable until recent times. Below, we will also show the chironomid-inferred mean July air temperatures for this lake using the new training set in Chapter 4 and compare it to the original reconstruction presented in this Chapter 6 (Figure 2).

The climatic history at Lake JR01 from the Boothia Peninsula was also assessed (Chapter 7). Of the three lakes studied, Lake JR01 has the highest overall chironomid production, and contained a larger relative abundance of the warmer-tolerant chironomid taxa, such as those from the subfamily Tanypodinae, although overall species composition remained similar to that of the other two Arctic lakes. Sediment organic and biogenic silica content as well as pollen concentrations were also high at Lake JR01 when compared to other sites in the Arctic. The new northern North American chironomid training set developed in Chapter 4 was primarily used in this study to infer past mean July air temperatures, as was the Barley et al. (2006) training set for comparison to the previous studies. Overall, aquatic and terrestrial production was highest prior to 5.5ka. Inferred temperatures were also highest in the early Holocene, and then decreased until ~5.0ka. The mid- to late-Holocene was a cooler, less productive time until ~1.0ka, where inferred temperatures cooled again. No recent warming is inferred from the chironomid assemblage, however overall production at this lake did increase in the last 150 years. Chironomid inferred temperatures remain up to 2°C degrees colder in the last 150 years than the warmest temperatures inferred during the early Holocene.

Prior to reconstructing mean July air temperature using the new chironomid based training set (Chapter 4), fossil data from Lakes WB02, KR02 and JR01 were passively plotted in the ordination space of the canonical correspondence analysis (CCA) for the training set (Figure 1). The distribution of the fossil samples on the ordination diagram in relation to the environmental gradients demonstrates which environmental variables are most closely related to the changes in chironomid assemblages through time. At Lakes WB02 and JR01 the fossil assemblages primarily ordinate along the first axis of the CCA (Figure 1a and 1c) whereas the downcore assemblages from Lake KR02 primarily ordinates along the secondary CCA axis but also along the first axis (Figure 1b). At all three lakes, the fossil assemblages ordinate to the right of the diagram, indicating that the fossil assemblages from all three lakes are along to colder end of the environmental gradient of the modern dataset. This is to be expected as the temperature gradient in the modern data set, which includes sites from northern British Columbia and Québec, is larger than the range of temperatures that are expected over the Holocene at the three study sites. When we look at the trajectory of the downcore fossil assemblages for all three lakes, it is apparent that there is a change through time in the species assemblage along the first axis of the CCA with the older assemblages ordinating on the warmer end of the gradient. However, as both JTemp and depth are strongly loaded on the first axis, it is possible that lake depth is also affecting the fossil assemblages at these lakes. Untangling the effect of multiple influential environmental variables on chironomid assemblages through time will be the focus of future chironomid work. Furthermore, as the fossil samples are clustered together it is impossible to exclude the influence of environmental variables that are strongly loaded on the second axis on the downcore chironomid assemblages. At Lake KR02 (Figure 1b) the downcore chironomid assemblages appear to be primarily influenced by environmental factors aligned with the second axis, such as lake water pH and conductivity, as indicated by the spread of fossil assemblage samples along the second axis. Unfortunately, these environmental variables cannot be reconstructed through time with any certainty using the new transfer function (Chapter 4) as these parameters only explained a small portion of the variance of the chironomids population in the training set lakes.

Passively plotting downcore fossil data on the ordination space of the training set CCA demonstrated that there is a relationship between changes in temperature and the fossil chironomid assemblages at all three lakes, but the length of environmental gradients in the training sets tend to be longer than those inferred at any given lake through time. This gives us confidence that the modern data provide a suitable modern training set for these cores. Previous work has suggested that the Arctic may have been very warm in the early Holocene, and we can be assured that we have sufficient data available to be able to reconstruct these conditions.

The new chironomid based training set, developed in Chapter 4, was used to reconstruct "updated" past mean July air temperatures from Lake WB02 and Lake KR02, and compare these revised temperature profiles to those originally presented in Chapters 5 and 6 (Figure 2). We will also use this new training set to infer past temperatures for two other sequences from the treeline region of the Northwest Territories (Macdonald et al., 2009) and Yukon (Bunbury and Gajewski, 2008) to see if this new transfer function provides reasonable results for both treeline and Arctic lakes and also to see if in these regions better analogues to the downcore chironomid assemblages could be found using our larger training set (Figure 2). The original chironomid-based temperature reconstructions for these two treeline lakes were generated using inference models that used one or a combination of the individual training sets incorporated into our new, larger training set presented in Chapter 4 (MacDonald et al., 2009; Bunbury and Gajewski, 2009).

The squared chord distances (SCDs), which measure how closely a modern fossil community resembles the downcore fossil assemblage, are generally smaller using this "new" training set (Figure 2). The SCDs are most noticeably improved during the colder mid- to late Holocene (past ~5ka) in the two northern sites, Lake WB02 and Lake KR02. Using a larger training set appears to provide better modern analogues for a greater range of past environmental conditions than the geographically restricted training sets.

For all lakes, with the exception of Lake S41, the new inference model reconstructed cooler temperatures than did the original inference models (Figure 2). This was expected, since the new training set covers a larger mean July air temperature gradient and includes a larger number of lakes from the Canadian Arctic Archipelago than the other training sets. These results demonstrate that using inappropriate training sets can lead to a general overestimation (or presumably underestimation in other areas) of past temperatures.

At both Lake KR02 and Lake JR01 the overall temperature profiles using the Barley et al. (2006) and the new Chapter 4 training set are quite similar, although the actual inferred temperatures are colder using the larger training set (Figure 2). However the revised temperature reconstructions at Lake WB02, Upper Fly Lake and Lake S41 are different than the originally presented ones.

Lake WB02's originally inferred past mean July air temperatures were considered poor due to the lack of good modern analogues in the training set used. The revised temperature profile, using the new training set is quite different from the original, and indicates warmer early Holocene temperatures (up to 8°C) prior to 6.0ka, followed by a cool period where inferred temperatures remained around 6°C until ~1.0ka (Figure 2). Temperatures rapidly cooled again at 1ka, increased starting at 0.5ka but remained variable from 0.15ka to recent times. Maximum temperatures over the last 150 years remained lower than those inferred for the early Holocene. This new temperature profile supports the original conclusions regarding the qualitative climatic history of Lake WB02, which were made based on the other lines of evidence from the same sediment sequence. The results of this analysis also support our conclusion that the Barley et al. (2006) inference model was not appropriate for reconstructing past environmental conditions at this cold polar desert lake.

The Upper Fly Lake temperature reconstruction using the new inference model indicates a cooling from ~4ka until a recent warming over the last 150 years, whereas the original reconstruction indicates a slight warming from 4ka to recent times (Figure 2). Similarly, the Lake S41 new reconstruction indicates a warming until ~1.5ka, followed by a gradual cooling, which is similar to the biogenic silica profile for this lake (not shown), but which is different from the original temperature reconstruction that indicated a continual warming from 2ka to recent times (Figure 2). For our purposes, it is sufficient to note that these empirically derived reconstructions depend on the modern-day calibration data used, and as we continue to gather more modern data and improve our knowledge of modern-day organism-environment relationships, this will impact our understanding of the past as well.

At the same time, attempting to quantify past conditions in multi-proxy paleoenvironmental studies can identify unusual or puzzling results and contradictions (e.g., as noted in lake WB02) that will signal to us that our understanding of the ecology of the arctic ecosystems is incomplete.

In studies where pollen and diatom assemblages were examined in addition to the chironomid assemblages, there is overall agreement between the interpretation of the production profiles of these three groups or organisms. Interpretations of the changes in diatom, pollen and chironomid assemblages through time are also largely coherent. However, the changes in inferred temperatures based on the pollen and the chironomid data at each lake are slightly divergent at different times in the Holocene, with the pollen-based temperature profiles predicting fewer smaller-scale changes and a smaller overall magnitude of change in mean July air temperatures over the Holocene than the chironomid-based temperature profiles. Peaks in chironomid production were also observed at Lakes KR02, Lake JR01 and at a number of sites across the Arctic at the onset of climatic changes, indicating that environmental instability directly affects chironomid communities.

An overall summary of the climate of the western Canadian Arctic using chironomids is now presented using the chironomid profiles from Chapters 5, 6 and 7, as is the mean July air reconstructions resulting from the inference model developed in Chapter 4 and discussed above. Overall, the early Holocene was warmer than present, with mean July air temperatures generally warmest prior to 6.5-5.5ka. Temperatures were cooler during the mid- to late Holocene and cooled further at around 1.0ka. A warming starting at ~0.5ka was recorded on Victoria Island, however, no warming was quantified at Lake JR01, although overall lake production did increase over the last 150 years at this lake. Maximum inferred mean July air temperatures over the last 150 years remain up to 2-3°C cooler than those inferred for the early Holocene. The overall climatic patterns inferred at these lakes through time are similar to those observed at a number of other sites across the regions, indicating the existence of broad climate influence on the ecosystems through time.

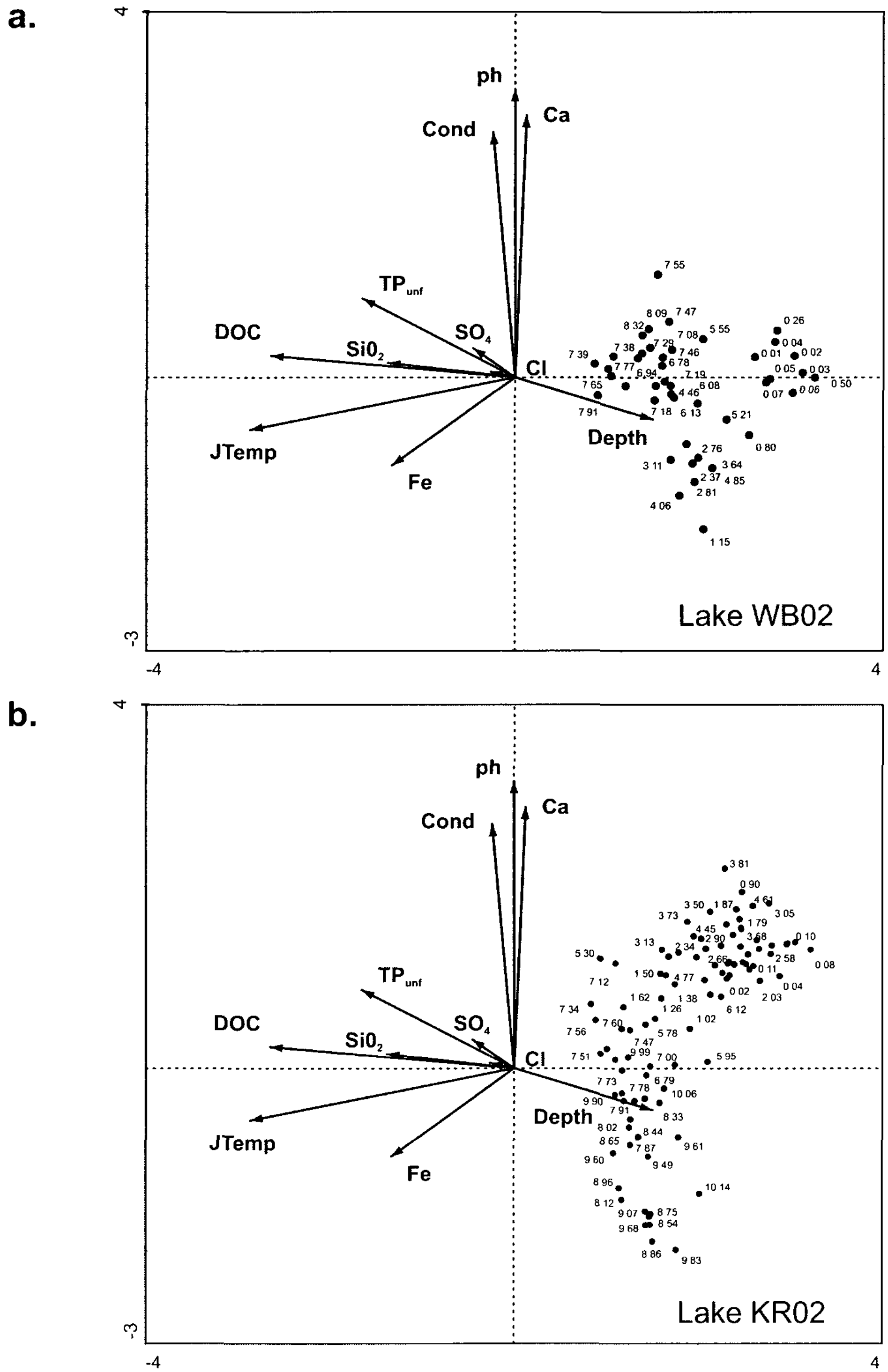

Figure 1 Canonical correspondence analysis of the modern training set data (Fortin [4]) with forward selected environmental variables and passively added downcore chironomid assemblages a. at Lake WB02, b. Lake KR02 and c. Lake JR01. Ages of selected downcore samples are in years ka. Acronyms for environmental variables are explained in text

c.

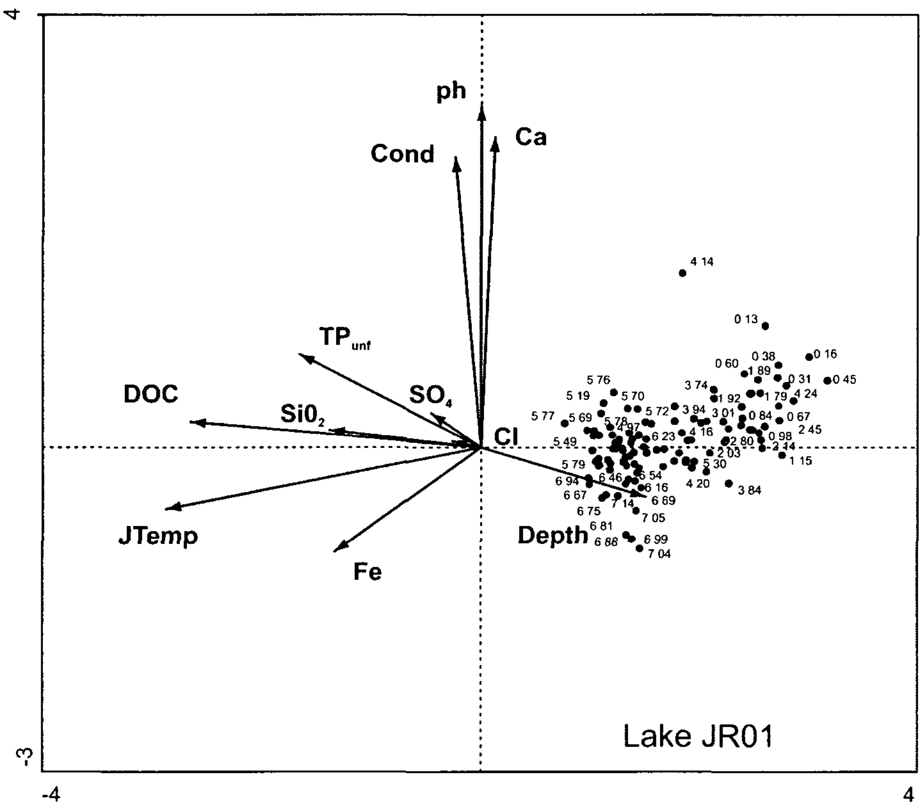

Figure 1 suite Canonical correspondence analysis of the modern training set data (Fortin [4]) with forward selected environmental variables and passively added downcore chironomid assemblages at a. Lake WB02, b. Lake KR02 and c. Lake JR01. Ages of selected downcore samples are in years ka. Acronyms for environmental variables are explained in text

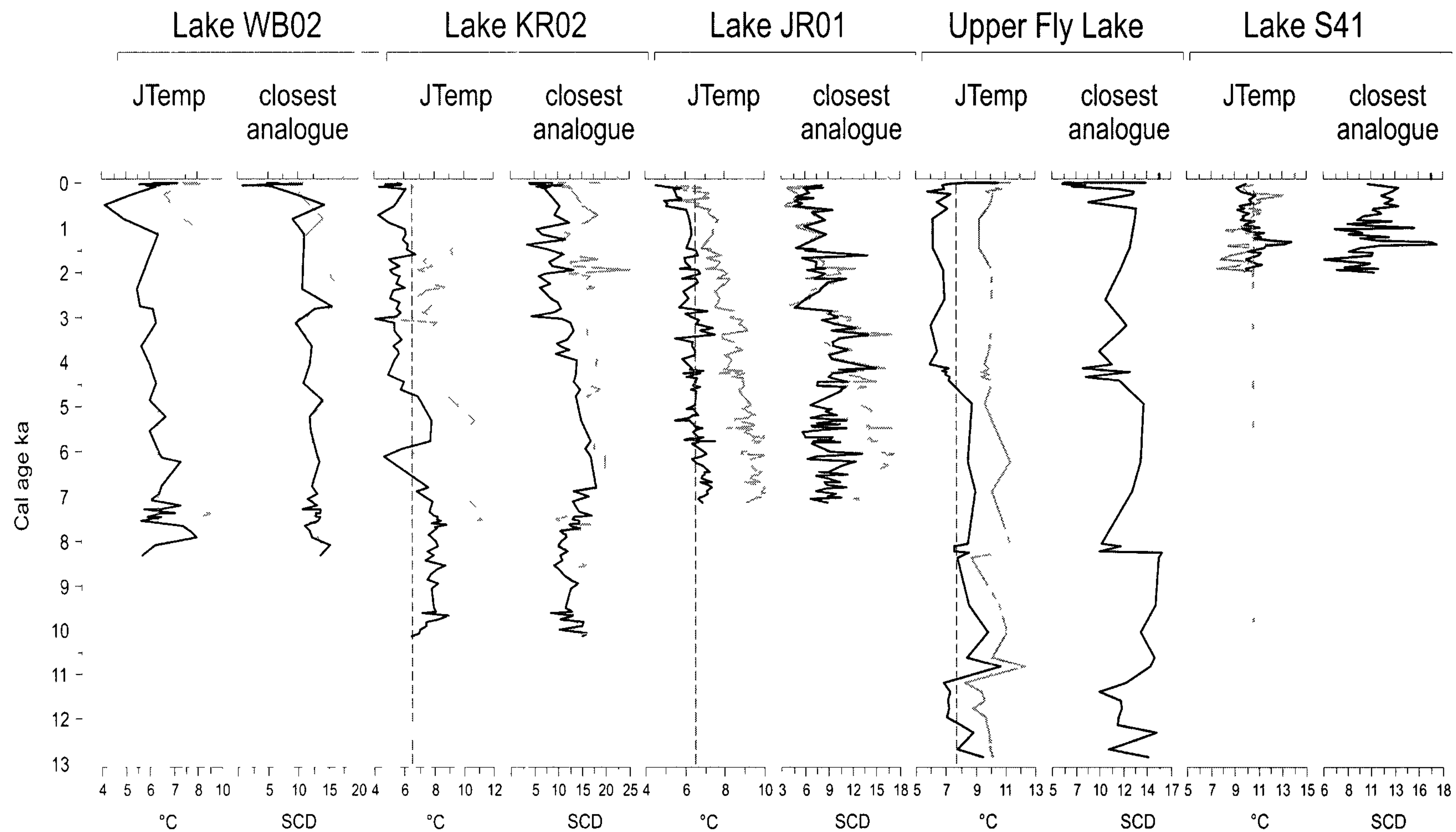

Figure 2 Mean July aır temperature (°C) reconstructions at Lake WB02, (Fortin and Gajewski, 2010 [5]), Lake KR02 (Fortin and Gajewskı, 2010b [6]), Lake JR01 (Fortin, *subm* [7]), Upper Fly Lake (Bunbury and Gajewski, 2009) and Lake S41 (MacDonald et al., 2009). Square chord distance (SCD) of the closest modern analogue is also presented. In grey (–) are the original results as presented ın the respective studies, ın black (–) are the results based on (Fortin, *subm* [7]). The dotted reference lines represent the average mean July aır temperature for each reconstruction

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Appendices

Appendix 1:
Chapter 2 environmental data

Lake name	Bsi weight%	loi550 weight%	loi950 weight%	dfc km	lat d.d	lon d.d.	elevation m	area km^2	conductivity $\mu S\ cm^{-1}$
Allen	0.71	5.09	12.07	18400	73.62	98.47	131	8.1600	68.0
BC01	10.37	15.16	3.39	3700	75.19	111.92	222	0.2370	5.0
BC02	7.25	14.22	1.96	4500	75.19	111.92	215	0.2220	7.0
BC03	1.04	5.38	0.59	5260	75.19	112.01	215	0.4092	12.0
CI01	0.62	3.26	23.35	4000	73.88	94.87	130	0.1375	150.0
CI07	0.27	1.17	1.95	6800	72.59	95.06	170	0.3188	80.0
CI08	0.85	6.40	5.87	3800	72.49	95.09	240	0.1250	170.0
CI09	1.68	8.43	6.96	3300	72.27	95.09	190	0.2131	30.0
CI14	2.31	8.15	7.56	10000	72.70	93.87	190	0.2131	2.5
CI17	0.71	4.95	12.17	1100	76.60	98.87	46	0.1250	80.0
CI20	1.90	10.32	1.25	6000	76.37	98.81	146	1.6125	50.0
CI22	0.80	5.67	1.24	9800	75.90	99.21	170	0.0844	90.0
CI23	1.65	13.17	4.32	5400	75.53	98.21	130	0.3125	70.0
CI26	0.54	6.69	1.26	7200	75.43	99.65	150	0.1104	10.0
CI29	0.26	0.22	0.05	3000	75.03	100.20	76	0.1772	30.0
CI31	0.47	8.20	11.86	1800	74.68	94.27	15	0.9063	2.5
CI32	1.09	7.51	20.54	3300	74.91	93.52	200	0.1650	10.0
CI34	1.84	11.04	7.20	20000	75.40	94.67	70	0.1963	29.0
Coal	0.51	8.46	2.02	16500	79.93	84.53	211	0.0050	1003.6
CV01	3.98	17.27	3.55	8320	79.93	82.95	350	0.0082	220.0
CV02	0.41	34.85	4.55	7930	79.92	82.93	350	0.0083	190.0
CV03	5.66	37.72	8.77	8100	79.92	82.94	350	0.0035	199.0
CV04	1.26	43.33	8.33	8200	79.92	82.93	350	0.0028	260.0
DV01	0.96	5.84	33.24	17500	74.98	90.36	240	0.0440	91.0
DV02	0.69	8.59	23.52	4400	74.93	88.68	134	0.0380	445.0
DV05	0.71	5.29	29.22	5600	75.52	92.05	64	0.1880	153.0
DV09	0.17	6.08	28.42	500	75.58	89.31	1	0.0782	100.0
E501	0.41	6.25	22.67	23900	79.33	82.54	855	0.3670	12.0
E503	3.38	35.31	7.58	7600	79.92	82.93	306	0.0050	26.0
E506	2.24	10.00	1.17	7000	80.57	84.47	520	0.1580	19.0
E507	2.78	37.25	2.02	4200	80.58	83.97	140	0.0001	21.0

Lake name	ph	depth m	DOC mg L^{-1}	TKN mg L^{-1}	TPunf mg L^{-1}	TPfilt mg L^{-1}	Cl mg L^{-1}	SiO_2 mg L^{-1}	SO_4 mg L^{-1}
Allen	7.70	4.00	0.700	0.103	0.0025	0.0025	1.7000	0.4800	2.30
BC01	6.58	11.30	0.500	0.070	0.0070	0.0070	0.4000	0.0380	0.50
BC-02	6.05	3.00	0.600	0.070	0.0080	0.0025	0.6000	0.5900	0.60
BC-03	6.34	2.00	1.000	0.050	0.0050	0.0025	1.1000	0.1520	0.90
CI01	7.60	2.10	0.716	0.100	0.0025	0.0025	1.2700	0.1150	2.22
CI07	7.77	5.50	1.820	0.150	0.0120	0.0060	4.5000	0.4700	1.61
CI08	8.10	4.00	3.204	0.370	0.0240	0.0025	3.8700	0.0580	25.05
CI09	8.20	4.00	0.537	0.090	0.0025	0.0025	0.8800	0.0380	1.62
CI14B	8.13	5.00	0.250	0.050	0.0025	0.0025	0.0500	0.0015	0.05
CI17	7.97	3.50	1.260	0.150	0.0025	0.0025	1.9000	0.3700	3.70
CI20	8.23	9.00	0.250	0.070	0.0025	0.0025	1.0200	0.1200	1.32
CI22	8.07	8.00	1.022	0.190	0.0220	0.0025	0.3900	2.1000	7.54
CI23	7.97	9.50	0.512	0.090	0.0025	0.0025	0.8300	0.1380	0.36
CI26	7.37	6.00	0.250	0.060	0.0025	0.0025	0.0500	0.0015	0.05
CI29	7.77	6.50	1.048	0.160	0.0025	0.0025	8.5400	0.2100	1.17
CI31	7.70	17.00	0.250	0.080	0.0025	0.0025	0.0500	0.0015	0.05
CI32	7.80	8.00	0.250	0.010	0.0025	0.0025	0.2800	0.0015	0.05
CI34	7.83	4.50	0.250	0.080	0.0025	0.0025	0.7000	0.0015	0.70
Coal	8.30	1.40	10.560	0.448	0.0098	0.0040	113.5000	0.8000	25.54
CV01	7.77	7.61	4.200	0.320	0.0110	0.0060	1.6000	0.8600	43.00
CV02	7.74	3.20	1.400	0.150	0.0025	0.0025	0.6000	0.5400	45.00
CV03	8.12	3.90	3.900	0.280	0.0110	0.0060	1.1000	0.6200	49.00
CV04	8.16	3.77	3.600	0.270	0.0100	0.0060	1.2000	0.7300	75.00
DV01	8.40	4.50	2.200	0.054	0.0025	0.0025	1.6400	0.2800	1.10
DV02	7.90	7.50	1.100	0.072	0.0025	0.0025	4.2000	1.2800	395.00
DV05	8.60	10.00	0.800	0.033	0.0025	0.0025	2.3000	0.2800	1.30
DV09	8.40	9.33	2.100	0.056	0.0025	0.0025	2.9000	0.3000	5.90
E501	6.60	34.00	1.000	0.257	0.0130	0.0083	0.6000	0.1000	0.50
E503	7.10	3.50	4.900	0.411	0.0130	0.0083	2.2000	2.2500	73.30
E506	7.00	14.00	0.700	0.065	0.0025	0.0025	1.3000	0.8800	2.10
E507	7.10	3.30	5.100	0.322	0.0210	0.0054	1.8000	1.7800	2.20

Lake name	Chl *a* mg L^{-1}	Ca mg L^{-1}	Fe mg L^{-1}	K mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	temp °C	vegetation	mineral
Allen	0.2000	12.00	0.0590	0.2000	4.400	0.800	4.8	SG	QC
BC01	**0.5395**	0.17	0.0210	0.0890	0.176	0.360	4.4	CBC	Qco
BC-02	**0.5395**	0.23	0.2700	0.1600	0.250	0.400	4.4	CBC	Qco
BC-03	**0.5395**	0.36	0.0190	0.1580	0.370	0.630	4.1	CBC	Qco
CI01	0.7102	22.00	0.0260	0.2200	3.900	0.670	4.5	CHB	C
CI07	0.9014	16.00	0.0480	0.2900	5.900	1.600	5.4	CBC	G
CI08	1.0341	28.00	0.0620	0.6600	13.200	2.200	5.2	G	G
CI09	0.6084	6.30	0.0290	0.1490	2.100	0.550	5.4	G	G
CI14B	0.4189	0.08	0.0020	0.0080	0.109	0.035	5.2	G	C
CI17	0.6913	17.50	0.0610	0.5100	2.500	1.780	5.0	PDS	Qco
CI20	0.7745	13.40	0.0440	0.1020	1.150	0.690	4.6	RG	QC
CI22	0.8214	23.00	1.0600	0.6900	2.900	0.490	4.6	RG	QC
CI23	0.7961	18.90	0.0580	0.1110	0.460	0.650	4.5	CHB	CQ
CI26	0.5456	0.23	0.1260	0.0180	0.007	0.035	4.5	RG	C
CI29	1.3201	1.09	0.0790	0.3700	1.110	4.000	4.8	RG	Qco
CI31	0.6608	0.50	0.0050	0.0410	0.164	0.140	4.2	CHB	C
CI32	0.6071	2.10	0.0030	0.0150	0.144	0.180	4.3	CHB	C
CI34	1.0611	4.20	0.0030	0.0600	0.790	0.340	4.5	G	CQ
Coal	0.5000	45.20	**0.0600**	9.7400	7.100	100.360	6.5	PDS	Q
CV01	**0.5395**	30.00	0.0040	1.4300	6.600	3.100	5.7	G	Q
CV02	**0.5395**	24.00	0.0030	0.5200	6.800	1.340	5.7	G	Q
CV03	**0.5395**	27.00	0.0040	1.4300	9.800	1.690	5.7	G	Q
CV04	**0.5395**	35.00	0.0050	1.7600	**5.250**	2.300	5.7	G	Q
DV01	0.0500	29.00	0.0030	*0.0005*	4.800	0.700	4.3	CHB	C
DV02	0.0500	140.00	0.0110	0.4000	17.200	2.300	4.8	CHB	CQ
DV05	0.0500	24.00	0.0040	*0.0005*	4.300	0.900	4.5	PDS	C
DV09	0.2000	27.00	0.0100	0.2000	5.200	1.900	4.9	CHB	CQ
E501	0.4000	4.00	0.1700	0.2000	0.700	0.200	2.9	PDS	C
E503	0.0500	57.00	0.0550	0.9000	11.400	2.600	5.7	G	Q
E506	0.4000	3.00	0.0068	*0.0005*	0.600	0.600	4.3	CHB	Qco
E507	1.2000	52.00	0.0940	3.6000	11.000	54.400	6.2	G	Qco

Lake name	Bsi weight%	loi550 weight%	loi950 weight%	dfc km	lat d.d	lon d.d.	elevation m	area km^2	conductivity $\mu S\ cm^{-1}$
E508	1.61	20.18	1.64	11800	80.81	84.16	170	0.1600	50.0
E509	12.03	21.13	1.84	16800	80.83	84.45	400	0.0230	43.0
E510	1.08	29.45	2.69	17800	80.75	84.68	290	0.1370	39.0
E511	3.27	9.15	1.40	9500	79.55	87.91	635	0.1950	31.0
E515	1.78	12.04	1.50	10300	79.65	87.75	205	0.2110	41.0
E516	2.33	7.72	0.77	8000	79.69	87.51	270	0.6330	344.0
JR01	0.47	6.58	15.12	24000	69.90	95.07	120	0.2100	220.0
JR02	1.79	18.36	18.45	30000	69.92	94.97	150	2.1000	198.0
JR05	0.56	4.76	8.29	26000	69.87	95.00	130	0.0900	10.0
JR06	3.16	26.48	14.97	24000	69.87	94.92	140	0.1350	39.00
KR01	2.62	6.94	2.56	54400	71.34	113.82	171	4.3425	34.2
KR02	11.24	47.95	4.09	58100	71.34	113.78	229	0.008	79.0
KR04	3.63	28.81	12.99	52500	71.31	113.94	175	1.0375	9.8
KR06	1.41	9.08	19.07	51000	71.32	113.97	189	0.283	18.7
KR07	3.73	44.67	10.31	55100	71.36	113.81	196	0.3600	154.8
KR08	4.64	10.56	16.43	62000	71.31	113.67	190	0.1250	420.0
MB01	1.53	15.65	7.94	52400	69.80	112.07	295	0.0784	270.0
MB02	1.07	9.01	8.56	52400	69.80	112.08	281	0.0800	280.0
MB03	1.91	11.16	11.39	52400	69.80	112.07	284	1.2074	280.0
SL01	4.56	6.66	1.56	57400	68.58	91.94	198	0.3644	4.0
SL02	6.45	8.15	1.56	58200	68.57	91.96	192	0.1105	16.0
SL03	0.29	1.26	0.41	56700	68.58	91.92	196	0.0117	11.0
SL04	8.14	7.02	1.67	56000	68.58	91.91	189	0.0748	20.0
SL05	8.29	10.62	3.72	54500	68.59	91.88	181	0.0208	14.0
SL06	4.16	12.50	0.60	55300	68.60	91.95	190	0.0342	15.0
Twobasin	1.03	9.63	1.72	13800	79.93	84.67	138	0.0030	569.2
WB01	0.51	11.44	6.24	17700	72.29	109.99	137	1.8725	139.0
WB02	3.02	13.42	8.27	17900	72.29	109.97	150	0.0231	88.0
WB04	2.94	23.96	6.04	18500	72.28	109.94	147	0.0874	75.0
WB05	0.67	3.14	26.42	17300	72.29	109.83	270	1.5350	99.0
WB06	0.65	3.86	18.25	15300	72.31	109.87	305	0.4400	97.0
Wolf	1.97	7.02	2.09	22200	73.58	98.48	151	0.4069	65.0

Lake name	ph	depth m	DOC mg L^{-1}	TKN mg L^{-1}	TPunf mg L^{-1}	TPfilt mg L^{-1}	Cl mg L^{-1}	SiO_2 mg L^{-1}	SO_4 mg L^{-1}
E508	7.60	2.60	2.700	0.149	0.0080	0.0025	1.4000	1.4000	4.30
E509	7.10	4.00	2.400	0.144	0.0060	0.0025	0.9000	1.2000	1.80
E510	7.20	9.00	2.400	0.198	0.0080	0.0025	1.2000	1.1000	2.10
E511	7.40	11.00	0.250	0.078	0.0070	0.0025	0.5000	1.7100	8.10
E515	7.40	12.00	2.600	0.209	0.0025	0.0025	3.5700	0.7000	5.40
E516	7.70	3.00	13.500	1.100	0.0060	0.0025	3.6000	1.1200	111.00
JR01	8.10	5.40	4.700	0.810	0.0400	0.0100	5.1000	1.2100	2.40
JR02	8.00	3.00	3.100	0.720	0.0300	0.0100	3.0000	0.6040	0.88
JR05	7.30	4.50	0.800	0.130	0.0200	0.0025	0.4000	0.0547	0.34
JR06	7.10	4.00	1.700	0.190	0.0200	0.0100	0.7000	0.0770	0.45
KR01	7.70	5.00	**2.034**	0.120	0.0070	0.0025	0.9000	0.6900	3.40
KR02	7.36	6.10	**2.034**	0.140	**0.0106**	0.0020	0.7000	0.9500	4.30
KR04	7.59	7.10	**2.034**	0.100	0.0130	0.0025	0.6000	0.2100	1.60
KR06	7.60	4.50	**2.034**	0.150	**0.0106**	0.0020	0.8000	0.1970	2.20
KR07	7.64	5.60	**2.034**	0.230	0.0100	0.0025	2.0000	1.5500	22.00
KR08	8.10	3.30	**2.034**	0.190	0.0070	0.0025	1.7000	1.6100	128.00
MB01	8.09	15.83	2.100	0.190	0.0050	0.0025	4.1000	1.1000	15.10
MB02	8.15	31.50	1.800	0.150	0.0025	0.0025	3.5000	0.6000	9.70
MB03	8.17	25.90	1.100	0.110	0.0025	0.0025	2.4000	0.8500	4.70
SL01	6.10	8.72	0.250	0.090	0.0090	0.0060	0.3000	0.0015	0.20
SL02	6.45	8.72	2.100	0.150	0.0110	0.0060	1.8000	0.0140	0.80
SL03	6.35	0.60	3.000	0.220	0.0160	0.0070	0.7000	0.2200	0.40
SL04	6.74	3.00	2.400	0.190	0.0130	0.0070	1.3000	0.1360	1.50
SL05	6.54	12.37	1.500	0.110	0.0080	0.0070	1.6000	0.0360	0.70
SL06	6.36	9.00	2.000	0.140	0.0110	0.0070	1.6000	0.1420	0.70
Twobasin	8.28	5.50	4.450	0.220	0.0040	0.0025	32.0167	1.2000	4.27
WB01	8.00	20.00	2.000	0.070	0.0710	0.0070	1.8000	0.4700	3.30
WB02	8.00	7.43	0.250	0.060	0.0650	0.0060	1.0000	0.4700	3.10
WB04	8.00	4.00	0.250	0.080	0.0120	0.0025	0.5000	0.5300	3.80
WB05	7.90	14.30	1.000	0.080	0.0160	0.0140	0.7000	0.3200	1.30
WB06	8.00	9.60	0.250	0.100	0.0130	0.0090	0.7000	0.4000	1.90
Wolf	8.40	6.00	1.300	0.150	0.0025	0.0025	1.5800	0.4900	4.10

Lake name	Chl *a*	Ca	Fe	K	Mg	Na	temp	vegetation	mineral
	mg L^{1}	mg L^{1}	mg L^{1}	mg L^{1}	mg L^{1}	mg L^{1}	°C		
E508	0 3000	52 00	0 0900	3 7000	11 000	49 900	5 8	NMC	Qco
E509	0 0500	8 00	0 0074	0 2000	0 600	0 400	4 3	NMC	Qco
E510	0 6000	8 00	0 1100	0 2000	0 700	0 500	5 6	CHB	Q
E511	1 4000	5 00	0 1650	0 2000	0 900	0 500	4 2	CMC	Q
E515	0 5000	8 00	0 0058	0 6000	2 200	2 300	6 2	G	Q
E516	0 0500	59 00	0 0490	0 7000	3 200	2 100	5 8	G	E
JR01	0 4400	42 40	0 0341	0 5570	21 700	2 110	7 1	PDS	C
JR02	0 3300	33 40	0 0334	0 6150	16 400	1 570	7 0	PDS	C
JR05	0 3400	1 73	0 0230	*0 0005*	0 760	0 186	7 1	PDS	C
JR06	0 5100	3 54000	0 0263	*0 0005*	1 2300	0 3720	7 1	PDS	C
KR01	0 2409	12 30	0 0720	0 2500	5 100	0 650	6 3	PDS	QC
KR02	0 3010	12 60	0 0330	0 1790	4 800	0 590	6 2	PDS	QC
KR04	0 1000	5 70	0 0350	0 1880	3 000	0 280	6 8	NS	QC
KR06	0 6788	5 70	0 0280	0 1530	2 800	0 250	6 8	NS	QC
KR07	0 3789	25 00	0 0440	0 5600	11 300	1 510	6 5	NS	QC
KR08	0 4507	78 00	0 0420	1 7600	18 800	1 530	6 4	PDS	QC
MB01	0 0959	27 00	0 0010	0 4600	16 300	1 280	7 3	PDS	C
MB02	0 1587	29 00	0 0010	0 4700	17 000	1 340	7 3	PDS	C
MB03	0 0587	28 00	0 0040	0 4600	17 000	1 280	7 3	PDS	C
SL01	0 6170	0 25	0 0060	0 0670	0 089	0 420	7 1	NS	G
SL02	0 1066	0 80	0 0340	0 4700	0 510	1 160	7 1	NS	G
SL03	0 1715	0 54	0 0920	0 5200	0 380	0 590	6 8	NS	G
SL04	0 1922	1 29	0 0370	0 6200	0 740	1 290	6 8	NS	G
SL05	0 1414	0 77	0 0180	0 3200	0 430	1 110	7 1	NS	G
SL06	0 1810	0 80	0 0500	0 3600	0 460	1 070	6 9	NS	G
Twobasin	0 2000	39 00	**0.0600**	4 6833	**5.250**	48 133	6 5	PDS	Q
WB01	1 3700	23 00	**0.0600**	1 4000	5 100	0 500	6 3	PDS	I
WB02	1 1300	27 00	**0.0600**	0 6000	5 000	0 600	6 2	PDS	I
WB04	1 3600	23 00	**0.0600**	0 3000	5 800	0 500	6 3	PDS	C
WB05	1 5300	14 00	**0.0600**	0 4000	7 100	0 500	6 1	PDS	C
WB06	1 6000	17 00	**0.0600**	0 0005	5 500	0 500	5 9	PDS	C
Wolf	0 6000	15 00	0 0030	0 3000	5 300	0 800	4 8	CHB	QC

Missing values were replaced, in **bold** by the average value for that environmental variable
Values below detection were replaced, in *italics*, by the mid-point between detection level and 0

Vegetation code

CBC	cryptogram barren complex
CMC	carbonate mountain complex
G	graminoid prostrate, dwarf shrub
NMC	non carbonate mountain complex
NS	non-tussock sedge, dwarf shrub
PDS	prostrate dwarf shrub, herb tundra
RG	rush, grass, forb, cryptogram tundra
SG	sedge, grass, moss, wetland

Mineral code

C	carbonate
QC	carbonate+quartz
E	evaporites
G	gneiss
I	maffic intrusive
Q	quartz
QC0	quartz and coal

Appendix 2:

Chapter 3 Arctic training set chironomid raw counts

Train set #	Lake #	Sample	TOTAL HC	CC	Chirind	Dicrind	Sergind	Sticind	Cory amb	Cory oli	Micpind
1	1	BC01-17-D0	42 5	7	0	0	0	0	0	0	11 5
1	2	BC02-A	61.5	4.75	0	0	0	0	0	0	4 5
1	3	BC03	50.0	7	0	0	0	0	0	0	14 5
1	4	CI20B	41.5	4	0	0	0	0	0	0	6 5
1	5	CI26B	59.0	2	0	0	0	0	0	0	4
1	6	COAL LB	179.0	4	1	0	2	2	0	1	45
1	7	CV01-D dr4	77.0	4	0	0	2	0	0	0	17 5
1	8	CV02-D0	179.0	4	0	0	47 5	0	0	0	16
1	9	CV03-D0	84.5	7	0	0	1 5	0	0	0	2
1	10	CV04-D0	93.5	6	0	0	7 5	0	0	0	0
1	11	DV09-D0	111.5	6.50	0	0	0	0	0	0	2 5
1	12	E501	65 0	3	0	0	0	0	0	0	4 5
1	13	E503 LC	91.0	1	0	0	4 5	0	0	0	14 5
1	14	E506	42 0	3.95	0	0	2	0	0	0	13 5
1	15	E508 LC	352.0	2.25	0	0	4 5	21 5	0	0	67 5
1	16	E510-GLEW	253.5	5	0	0	50	1	0	0	69 5
1	17	E511	45 5	6.4	0	0	0	0	0	0	0
1	18	JR05-B	63.5	2	0	0	0	15	0	0	1 5
1	19	JR06-B	132.5	2	2	0	6	0	18	6	4
1	20	KR04-GLEW	211 0	2 5	0	0	7 5	1 5	0	3	35
1	21	KR08-GLEW	37.0	1 5	0	0	1	2 5	0	1	2
1	22	MB01-D0	65 0	2	0	0	6	0	0	0	1
1	23	MB02-CORE2	58.0	2 5	0	0	0	0	0	0	2
1	24	MB03-CORE1	130.0	2	0	0	3	0	0	0	19 5
1	25	MR01-GLEW1	45.0	8	0	0	0	0	0	0	6 5
1	26	MR02-D0	185.0	4	0	0	11 5	0 5	0	3	28 5
1	27	SL01-D4	95.5	3.75	0	0	1	0	0	0	21
1	28	SL02 dr3	67.5	3	0	0	0	0	0	1	10
1	29	SL03-A1	69.5	5	2	0	0	11	0	0	0
1	30	SL04-A2	64.5	2	0	0	2	0	0	1	13 5
1	31	SL05-D0	86.0	1	0	0	6 5	0	0	0	8 5
1	32	SL06-D0	228 5	2	0	0	1	1	0	0	46 5
1	33	SP02	112 0	1	0	0	0	5	0	2	19 5
1	34	SP04	114 5	3	0	0	4	5	0	1	13
1	35	Two Bassin	114 0	4	0	0	7	5	0	0	32 5
1	36	WB01-K	72.5	5 25	0	0	11 5	0	0	0	3
1	37	WB04-B	117.5	1 5	0	0	3 5	4	0	0	24 5
1	38	WB06-A	60.0	5	0	0	7	0	0	0	6
2	39	E509	75.5	5	0	0	1	0	0	0	3
2	40	E507	57.5	5	1	0	10 5	0	0	0	0
2	41	HW06	77 5	10	0	0	1	0	0	0	3
2	42	HW05	55	5	0	0	5 5	0	0	0	3
2	43	HW01	70	5	1	0	7	0	0	0	1
2	44	E505	55	5	0	0	9	0	0	0	0
2	45	Ridge	69 5	5	0	0	3	0	0	0	19 5
2	46	E504	156	10	0	0	16	0	0	0	44
2	47	HW03	72 5	25	0	0	0	0	0	0	20
2	48	HW02	48	10	0	0	8	0	0	0	7
2	49	HW08	114	10	0	0	58 5	0	0	0	15
2	50	HW07	73 5	5	0	0	30	0	0	0	3
2	51	E516	121 5	3	0	0	1	0	0	0	17 5

Lake #	Protind	Diamind	Pottind	Psedind	Mondind	Abisind	Bril&E	Cory&T	Cric&O	Doit&P	Euki&T
1	0	0	0	13 5	0	0	0	0	0	0	0
2	0	0	0	14	0	0	0	0	9 5	0	0
3	0	0	0	17 5	0	0	0	0	0	0	0
4	0	0	0	5 5	0	0	0	0	0	0	0
5	0	0	0	7	0	0	0	1	0 5	0	0
6	0	0	0	0	0	0	0	0	12	0	0
7	0	0	0	29	0	0	0	1	7 5	0	0
8	0	0	0	4	0	0	0	13	46	0	0
9	0	0	0	0	0	0	0	2	8	0	0
10	0	0	0	0	0	0	0	6	33 5	0	0
11	0	0	0	4	0	0	0	0	0 5	0	0
12	0	0	0	6	0	0	0	0	3	0	0
13	0	0	0	0	0	0	0	7	27 5	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	13	0	0
16	0	0	0	1 5	0	0	0	8	14 5	0	0
17	0	0	0	0	0	0	0	0	0	0	0 5
18	0	0	0	0 5	0	1	0	3	0 5	0	0
19	0	0	0	0	0	0	0	0	7	0	0
20	0	0	0	1	0	3	0	9	6	0	0
21	0	0	0	0	0	2	0	0	0 5	0	0
22	1	0	0	4	0	9	0	1	5 5	0	0
23	1	0	0	0 5	0	6	0	5	1 5	0	0
24	0	0	0	11	0	12	0	1	34 5	0	0
25	1 5	0	0	7 5	0	4 5	0	0	0	0	0
26	1	0	0	6	0	35	0	3	13 5	0	0
27	0 5	0	0	6 5	0	22	0	1	3	0	0
28	3	0	0	1 5	0	0 5	0	2	2	0	0
29	0	0	0	0	0	0	0	1	19 5	0	0
30	0	0	0	0	0	6 5	0	1	0	0	0
31	1	0	0	3	0	4	0	2	13 5	0	0
32	4	0	0	5	0	21 5	0	2	2	0	0
33	0	0	0	4	0	13	0	2	7 5	0	0
34	1	0	0	1	0	3	0	0	1	0	0
35	0 5	0	0	0	0	0	0	0	0 5	0	0
36	0 5	0	0	11 5	0	9	0	0	18	0	0
37	1	0	0	2 5	0	24	0	0	2 5	0	1
38	0	0	0	9	0	0 5	0	0	5 5	0	0
39	0	0	0	0	0	0	0	0	2 5	0	0
40	0	0	0	0	0	0	0	1	15	0	2
41	0	0	0	0	0	0	0	1	16	0	0
42	0	0	0	2 5	0	0	0	0	0 5	0	0
43	0	0	0	0	0	0	0	1	3 5	0	0
44	0	0	0	0	0	0	0	2	10 5	0	0
45	0	0	0	0	0	0	0	0	0	0	0
46	0	0	6	33 5	0	0	0	0	13	0	0
47	0	0	1	6	0	0	0	0	1	0	0
48	1	0	0	5	0	0	0	0	3 5	0	0
49	0	0	0	19	0	0	0	0	1 5	0	0
50	0	0	0	2 5	0	0	0	0	1	0	0
51	0	0	0	4	0	0	0	1	4	0	0

Lake #	Heteind	Hydr&O	Limno&P	Mescind	Metrind	Parlind	Park nig	ParkindB	Park tri	Pare&P
1	0	5 5	0	0	0	0	0	0	0	0
2	6	6	0	0	0	0	0	0	0	0
3	0	9	0	0	0	0	0	0	0	0
4	0	21 5	0	0	0	0	0	0	0	0
5	0	37 5	0	0	0	3	0	0	0	0
6	34 5	4 5	0	0	0	9 5	0	0	1	0
7	0	0 5	0	0	0	0	4	0	0	0
8	0	0	0	0	0	1	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
11	56 5	8	0	0	0	22 5	0	0	0	0
12	25 5	3 5	0	0	0	1	0	0	0	0
13	0	0 5	0	0	0	0	0	0	0	0
14	1	0	0	0	0	5	10 5	0	0	0
15	54	1	0	0	0	4 5	0 5	0	0	0
16	10 5	0	0	0	0	19 5	0	0	0	0
17	2 5	41	0	0	0	0	0	0	0	0
18	0	0	0	0	0	1	0	0	0	0
19	1	3 5	0	0	0	6	0	0	0	0
20	11 5	0	0	0	0	1 5	0	0	0	0
21	14	0	0	0	0	0	0	0	1	0
22	0	1	0	0	0	9 5	1 5	0	0	0
23	23	1	0	1	0	3	1 5	0	0	0
24	0 5	1 5	0	0	0	2 5	0	0	0	0
25	0 5	2 5	0	0	0	5 5	7 5	0	0	0
26	1	0	0	0	0	19 5	0 5	0	0	0
27	10	0	2	0	0	5	0	0	0	0
28	20	0	0	0	0	0 5	0 5	0	3 5	0
29	0	0	0	0	0	0	0	0	1	0
30	3	0	0	1	0	0	0	0	0	0
31	19	0	0	0	0	3 5	1 5	0	0	0
32	42	4 5	0	1 5	0	6	4	0	0	0
33	12 5	0	0	1	0	4 5	2	0	0	0
34	0 5	0	0	0	0	51 5	1	0	0	0
35	11 5	0	0	0	0	1 5	0	0	0	0
36	0 5	0	0	0	0	1	0	0	0	0
37	5 5	0	0	0	0	8	2	0	0	0
38	8	2 5	0	0	0	6 5	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0
41	0	27 5	1	0	0	0	0	0	0	1
42	0	0	0	0	0	0 5	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0
44	0	4 5	0	0	0	0 5	0	0	0	0
45	2 5	0 5	1	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0
47	20	2 5	0	0	0	0	0	0	0	0
48	0	0	0	0	0	3	0	0	0	0
49	0	0	0	0	0	1 5	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0
51	19	5 5	1 5	0	0	39 5	2	0	0	0

Lake #	Propınd	PsecındE	Pses&S	*ZalA&Ba*	*ZalB&Ba*	*ZalB&Br*	trpenta	Procınd	fchıron
1	0	0	0	0	0	0	0	0	7
2	0	0	0	0	0	0	0	0	4 5
3	0	0	0	0	0	0	0	0	1 5
4	0	0	0	0	0	0	0	0	3
5	0	0	0	0	0	0	0	0	1
6	0	1	0	0	0	0	18 5	6	12
7	0	0	0	1 5	0	0	1	0	5 5
8	0	0 5	0	3 5	0	0	1	0	20 5
9	0	0	0	4	0	0	3	3	3
10	0	0	0	13 5	0	0	5	2	5
11	0	0	0	0 5	0	0	0	0	5 5
12	0	0	0	0	0	0	0	0	9
13	0	0	0	4	4 5	0	0	1	4 5
14	0	0	0	0	0	0	0	0	1 5
15	0	0	0	0 5	0	0	34	10	10 5
16	0	1 5	0	0 5	0 5	3 5	7	0	10
17	0 5	0	0	0	0	0	0	0	1
18	0	0	0	0	1	0	5	5	1
19	0	6	0	2	1	1	9	6	13 5
20	0	1	0	0	0	0	15	8	12 5
21	0	0	0	0	0	0	0	0	3 5
22	0	1	0	0 5	0 5	2	1	0	5
23	0	2	0	1	1	0	0	0	2 5
24	0	0 5	0	0	0	0	0	0	13 5
25	0	0	0	0	0	0	0	0	5
26	0	1 5	0	3 5	1	2 5	0	0	9
27	0	0	0	1 5	1	0	0	0	0 5
28	0	0	0	1 5	5	0	0	1	4
29	0	0	0	0	0 5	0	3	0	8
30	0	0	0	1	0 5	0	5	2	4
31	0	0	0	3 5	2 5	0	1	0	3
32	0	2	0	4	8 5	0 5	3	2	10 5
33	0	0	0	4 5	2	0	7	1	5
34	0	1	0	1	2 5	0	3	0	11 5
35	0	0	0	0	0	0	12	7	3
36	0	0	0	0	0	0	0	0	9
37	0	0	0	0	6 5	0	0	0	4
38	0	0	0	0	0	0	0	0	5 5
39	0	0	1	1 5	0	0	0	0	16
40	0	5	0	0 5	0	0	0	2	8 5
41	0	0	0	0	0	0	0	0	24
42	0	0	0	0	0	0	2	1	8
43	0	0 5	0	1	0	0	1	0	25
44	0	0	0	3	0	0	0	0	14 5
45	0	0	0	0	0	0	3	4	7
46	0	0	0	0	0	0	1	0	11 5
47	0	0	0	0	0	0	0	0	11
48	0	0	0	1	0	0	0	0	2 5
49	0	0	0	0	0	0	0	0	6 5
50	0	1 5	0	0	0	0	0	3	1 5
51	0	0	0	0	0	0	0	0	16 5

Train set #	Lake #	Sample	TOTAL HC	CC	Chirind	Dicrind	Sergind	Sticind	Cory amb	Cory oli	Micpind	trtanyt
2	52	E515	50	1	0	0	0	0	0	0	11	3
2	53	CI17	57.5	5	0	0	0	0	0	0	4	7
2	54	CI18	242.5	5	0	0	174	0	0	0	6	5
2	55	CI16	100	5	0	0	3	0	0	0	0	0
2	56	CI15	163.5	5	0	0	5	0	0	0	55 5	35 5
2	57	CI22	151.5	10	0	0	0 5	0	0	0	19	28 5
2	58	CI23	78.5	5	0	0	0	0	0	0	25 5	24 5
2	59	CI25	185.5	5	0	0	13	0	0	0	35	19
2	60	CI27	123.5	5	0	0	6 5	0	0	0	39	21 5
2	61	DV07	132.5	10	0	0	7	0	0	0	29	25
2	62	DV05	94	5	0	0	8	0	0	0	44	26
2	63	DV06	123.5	15	0	0	17 5	0	0	0	17	12
2	64	DV08	52.5	5	0	0	0	0	0	0	22	24 5
2	65	DV02	56	10	0	0	5	0	0	0	18	12
2	66	DV04	77	10	0	0	0	0	0	0	10 5	3 5
2	67	CI34	59.5	15	0 5	0	1 5	0	0	0	14	4
2	68	CI33	116	5	0	0	6	0	0	0	70 5	19
2	69	CI32	196	5	0	0	0	0	0	0	129	59
2	70	CI31	99 5	5	0	0	0	0	0	0	41 5	13 5
2	71	Allen	81.5	15	0	0	0	0	0	0	5	7
2	72	DUO	87	5	12	0	0	3	0	0	3	22
2	73	Wolf	74	10	0	0	2 5	0	0	0	14	3
2	74	CI01	106	10	4	0	1	0	0	0	28	5
2	75	CI14	191	1 5	0	0	7 5	0	0	0	73	13 5
2	76	CI07	211.5	5	0	0	42 5	0	0	0	52	14
2	77	CI08	81	20	11	0	0	2	0	0	3	36
2	78	CI09	100.5	5	0	0	0	0	0	0	24	4
2	79	CI12	53 5	15	0	0	0	0	0	0	30	11
2	80	CI11	158	5	0	0	1	0	0	0	46	26
2	81	WB05	66 5	8	0	0	1	0	0	0	16 5	12
2	82	WB02	73	25	0	0	5	0	0	0	4	13
2	83	KR07	56	27	0	0	0	1	0	0	12	15 5
2	84	KR02	96	10	5	0	11 5	1	0	0	4	11
2	85	KR01	76	5	0	0	0	3	0	0	21	16
2	86	KR06	62	10	0	0	2	2	13	0	3	24
2	87	JR02	152	5	0	0	4 5	0	0	1	34 5	28
2	88	JR01	158 5	8	0	0	5	1	0	0	61	31

Lake #	Protind	Diamind	Pottind	Psedind	Mondind	Abisind	Bril&E	Cory&T	Cric&O	Doit&P	Euki&T
52	2	0	0	1	0	0	0	1	1 5	0	0
53	0	0	0	24	0	0	0	0	5	0	0 5
54	0	0	0	2 5	0	0	0	1	26	0	0 5
55	0	0	0	0	0	0	0	0	13	0	5
56	0	0	2	15 5	0	0	0	0	19 5	0	0 5
57	0	0	1	66 5	0	0	0	0	1	0	0
58	1 5	0	0	1	0	0	0	0	0	0	0
59	0	0	0	7	0	0	0	0	53	0	0
60	1	0	0	11	0	0	0	0	20 5	0	2 5
61	0	0	0	3	0	0	0	0	3	0	0
62	0	0	0	1	0	0	0	0	2 5	0	0
63	0	0	0	1	0	0	0	0	4 5	0	0
64	0	0	0	1	0	0	0	0	2 5	0	0
65	0	0	0	13 5	0	0	0	0	1	0	0
66	0	0	0	4	0	0	0	0	2 5	0	0
67	0	0	0	3 5	0	0	0	0	5 5	0	0
68	0	0	0	4	0	0	0	0	0	0	0 5
69	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	11	0	0	0	0	4	0	0
71	4	1	3	7	0	9	0	1	6 5	0	5
72	0	0	0	0	0	0	0	1	10	0	0
73	0 5	0	0	7 5	0	19 5	0	0	11	0	0
74	2	0	0	6 5	0	2	0	2	10 5	0	1 5
75	4	0	0	7	0	40	0	0	2	0	0
76	1	0	0	6 5	0	59	0	0	6 5	0	0
77	0	0	0	0	0	0	0	2	1 5	1	0
78	5	0	0	11 5	0	26 5	0	0	0	0	0
79	0	0	0	5 5	0	0	0	0	0	0	0
80	3 5	0	0	10 5	0	33 5	0	0	2 5	0	0
81	2	0	1	16	0	9	0	0	1 5	0	0
82	0	0	0	1	0	5 5	0	4	6	0	0
83	0	0	0	0	0	0 5	0	0	0	0	0
84	0	0	0	0	0	5	0	0	0	0	0
85	0	0	0	1	2 5	2 5	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0
87	2 5	0	0	5 5	0	45 5	0	0	0	0	1
88	2	0	0	5 5	0	12	0	1	2 5	0	0

Lake #	Heteınd	Hydr&O	Lımno&P	Mescınd	Metrınd	Parlınd	Park nıg	ParkındB	Park trı	Pare&P
52	16 5	0	0	0	0	5	5	0	1	0
53	1	3	0	0	0	0 5	0	0	0	0
54	0	2 5	0	0	1	0	0	0	0	0
55	0	56 5	0	0	0	0	0	0	0	0
56	0	16	0	0	0	0	0	0	0	0
57	0	11 5	0	0	0	0	0	0	0	0
58	0	1	0	0	0	23 5	0	0	0	0
59	0	1	0	0	0	20 5	0	0	0	0
60	0	4 5	0	0	0	1	0	0	0	0
61	0	0	0	0	0	60	0	0	0	0
62	0	0	0	0	0	9	0	0	0	0
63	0	0	0	0	0	63	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0
66	12 5	0	0	0	0	39 5	0	0	0	0
67	7	10	0	0	0	0	0	0	0	0
68	0	1	0	0	1	6	0	0	0	0
69	0	0	0	0	0	1	0	0	0	0
70	5 5	7	0	0	0	12	0	0	0	0
71	4	5 5	0	0	0	11	0	0	0	0
72	0	0	1	0	2	0	0	0	0	0
73	1 5	4 5	0	0	1	1	0	0	0	0
74	1 5	19 5	0	0	2	3	0	0	0	0
75	2	2	0	0	0	24 5	4	0	1	0
76	0	0	0	0	0	6	2	0	0	0
77	0	0 5	0	0	0	0	0	9	5 5	0
78	3 5	3	0	0	0	15 5	3 5	0	0	0
79	0	3 5	0	0	0	2	0	0	0	0
80	0	5	0	0	0	19	1	0	0	0
81	1	0 5	0	0	0	0 5	0	0	0	0
82	0 5	0	0	0	0	2	0	0	0	0
83	2 5	0	0 5	0	0	13	0	0	0	0
84	0	0	0	0	0	12 5	0	0	0	0
85	20 5	0	0	0	0	1 5	0	0	0	0
86	1	0 5	1	0	0	0	0	0	0	0
87	0	0	0	0	0	16 5	1	0	0	0
88	2	0	0	0	0	20	0	0	0	0

Lake #	Propind	PsecindE	Pses&S	*ZalA&Ba*	*ZalB&Ba*	*ZalB&Br*	trpenta	Procind	fchiron
52	0	0	0	0	0	0	0	0	3
53	0	0	0	0	0	0	0	0	12 5
54	0	0	0	0	0	0	0	0	24
55	0	0	0	0	0	0	0	0	22 5
56	0	0	0	0	0	0	0	0	14
57	0	0	0	0	0	0	0	0	23 5
58	0	0	0	0	0	0	0	0	1 5
59	0	0	0	0	0	0	0	0	37
60	0	0	0	0	0	0	0	0	16
61	0	0	0	0	0	0	0	0	5 5
62	0	0	0	0	0	0	0	0	3 5
63	0	0	0	0	0	0	0	0	8 5
64	0	0	0	0	0	0	0	0	2 5
65	0	0	0	0	0	0	0	0	6 5
66	0	0	0	0	0	0	0	0	4 5
67	0	1	0	0	0	0	0	0	12 5
68	0	0	0	0	0	0	0	0	8
69	0	0	0	0	0	0	0	0	7
70	0	0	0	0	0	0	0	0	5
71	0	0	0	0	0	0	0	0	12 5
72	0	19 5	0	0	0	0	1	2	10 5
73	0	0	0	0	0	0	0	0	8
74	0	0	0	0	0	0	0	0	17 5
75	0	0	0	0	0	0	0	0	10 5
76	0	0	0	0 5	0	0	0	0	21 5
77	0	1 5	0	0	0	0	0	0	8
78	0	0	1	0	0	0	0	0	3
79	0	0	0	0	0	0	0	0	1 5
80	0	0	0	0	0	0	0	0	10
81	0	0	0	0	0	0	0	0	5 5
82	0	27	0	0	0	0	0	0	5
83	0	1 5	0	0	1	0	1	0	7 5
84	0	1 5	0	0	13	0	0	1	30 5
85	0	0	0	0	0	0	2	0	6
86	0	1	0	0	0	0	0	4	10 5
87	0	1 5	0	0 5	0	0	0	0	10
88	0	2	0	1 5	0 5	0	0	0	11 5

Training set #1 lakes are original to this manuscript

Training set #2 lakes are originally from Gajewski et al. (2005)

Taxon codes for Appendix 2

Chirind	*Chironomus* spp.
Dicrind	*Dicrotendipes*
Sergind	*Sergentia*
Sticind	*Stictochironomus*
Cory amb	*Corynocera ambigua*
Cory oli	*Corynocera oliveri*
Micpind	*Micropsectra*
trtanyt	*Tanytarsina other*
Protind	*Protanypus*
Diamind	Diamesa type
Pottind	Potthastia type
Psedind	*Pseudodiamesa*
Mondind	Monodiamesa
Abisind	*Abiskomyia*
Bril&E	*Brillia/Euryhapsis* spp.
Cory&T	*Corynoneura/Thienemanniellas* spp.
Cric&O	*Cricotopus/Orthocladius* spp.
Doit&P	*Doithrix/Pseudorthocladius* spp.
Euki&T	*Eukiefferiella/Tvetenia* spp.
Heteind	*Heterotrissocladius* spp.
Hydr&O	*Hydrobaenus/Oliveridia* spp.
Limno&P	*Limnophyes/Paralimnophyes* spp.
Mescind	*Mesocricotopus* spp.
Metrind	*Metriocnemus*
Parlind	*Paracladius*
Park nig	*Parakiefferiella nigra*-type
ParkindB	*Parakieffferiella sp B*-type
Park tri	*Parakiefferiella triquetra*-type
Pare&P	*Parametriocnemus/Paraphaenocladius* spp.
Propind	*Propsilocerus*
PsecindE	*Psectrocladius (Psectrocladius)*
Pses&S	*Pseudosmittia/Smittia* spp.
ZalA&Ba	*Zalutschia spA* (see Barley et al. 2006)
ZalB&Ba	*Zalutschia spB (see Barley et al. 2006)*
ZalB&Br	*Zalutschia spB (see Brooks et al. 2007)*
trpenta	Tribe Pentaneurini
Procind	*Procladius*
fchiron	unkown/unidentifiable chironomids

Appendix 3:

Chapter 4 taxonomical harmonization guide for the northern North American chironomid training set

	This study	Barley et al. 2006	Larocque et al. 2006	Wilson and Gajewski 2004	Fortin [3] & Gajewski et al. 2005	Porinchu et al. 2009
Abiskomyia	Abisind	Abisind	*Abiskomyia*	n/a	Abisind	Abisind
Ablabesmyia	Ablaind	n/a	*Ablabesmyia*	n/a	n/a	*Ablabesmyia*
Acamptocladius	Acamind	Acamind	n/a	n/a	n/a	n/a
Apedilum spp	Apedind	Apedind	n/a	n/a	n/a	n/a
Brillia/Euryhapsis spp	Bril&E	Bril&E	Brillia	n/a	n/a	n/a
Cardiocladius spp	Cardind	Cardind	n/a	n/a	n/a	n/a
Chaetocladius spp	Chaeind	n/a	*Chaetocladius*	n/a	n/a	n/a
Chironomus spp	Chirind	Chirind	*Chironomus anthracinus* *Chironomus plumosus*	Chironomus (CHIRO)	Chirind	*Chironomus anthracinus* *Chironomus plumosus*
Cladopelma spp	Cladind	Cladind	*Cladopelma*	*Cladopelma* CLADO	n/a	Cladopel
Cladotanytarsus spp	Clatind	Clat man	*Cladotanytarsus*	*Cladotanytarsus mancus* grp CLTAN	n/a	Clad man
Constempellina	Consind	n/a	*Constempellina*	n/a	n/a	n/a
Corynocera ambigua-type	Cory amb	Cory amb	*Corynocera ambigua*	*Corynocera ambigua*	Cory amb	*Corynocera ambigua*
Corynocera oliveri-type	Cory oli	Cory oli	*Corynocera oliveri*	*Corynocera oliveri* COROL	Cory oli	*Corynocera oliveri*
Corynoneura/Thienemanniella spp	Cory&T	Cory&T	*Corynoneura* spp	*Corynoneura* (CORYN) *Corynoneura/Thienemanniella* CT	Cory&T	Corynoneura
Cricotopus/Orthocladius spp	Cric&O	Cric&O Orthind2	*Cricotopus* *Orthocladius*	*Cricos/Ortho (C cylindraceus*-t) (COCYL) *Crico/Ortho (C tremulus*-t)(COTRE) *Crico/Ortho* (CO) *Orthocladius* spp ORTHSPP	Cric&O	*Cricotopus* *Orthocladius*
Cryptochironomus	Crytind	Crytind	*Cryptochironomus*	n/a	n/a	n/a
Cryptotendipes	Crypind	Crypind	*Cryptotendipes*	n/a	n/a	n/a
Cyphomella/Harnischia/Paracladopelma spp	Cyph&HP	Cyph&HP	n/a	n/a	n/a	n/a
Derotanypus	Deroind	Deroind	n/a	n/a	n/a	n/a
Diamesa spp	Diamind	Diamind	n/a	n/a	Diamind	n/a
Dicrotendipes spp	Dicrind	Dicrind	*Dicrotendipes*	*Dicrotendipes* DICRO	n/a	Dicrind
Doithrix/Pseudorthocladius spp	Doit&P	Doit&P	*Pseudorthocladius*	n/a	Doit&P	n/a
Einfeldia spp	Einfind	Einfind	*Einfeldia*	n/a	n/a	n/a

	This study	Barley et al. 2006	Larocque et al. 2006	Wilson and Gajewski 2004	Fortin [3] & Gajewski et al. 2005	Porinchu et al. 2009
Endochironomus spp	Endoind	Endoind	*Endochironomus* *Endochironomus tendens* Endochir Impar	*Endochironomus* ENDO	n/a	n/a
Eukieffferiella/Tvetenia spp	Euki&T	Euki&T	*Eukiefferiella*	*Eukiefferiella* EUKF	Euki&T	*Eukiefferiella*
Georthocladius spp	Georind	n/a	*Georthocladius*	n/a	n/a	*Georthocladius*
Glyptotendipes spp	Glypind	Glypind	*Glyptotendipes* *Glyptotendipes types 2*	*Glyptotendipes* GLYO	n/a	Glypind
Heterotanytarsus	Hettind	Hettind	*Heterotanytarsus*	n/a	n/a	*Heterotanytarsus*
Heterotrissocladius spp	Heteind	Heteind	*H grimshawi* *H marcidus* *H maeri* *H subpilosus*	*Heterotrissocladius* HETER	Heteind	*Heterotrissocladius* spp
Hydrobaenus/Oliveridia spp	Hydr&O	Hydr&O	*Hydrobaenus* *Oliverdia*	n/a	Hydr&O	Hyd/Oliv
Labrundinia	Labrind	Labrind		n/a	n/a	n/a
Lasiodiamesa	Lasiind	Lasiind	n/a	n/a	n/a	n/a
Lauterborniella/Zavreliella spp	Laut&Z	Laut&Z	n/a	n/a	n/a	n/a
Limnophyes	Limnind	Limnind	*Limnophyes*	n/a	Limno&P	*Limnophyes*
Mesocricotopus	Mescind	Mescind	*Mesocricotopus*	n/a	Mescind	Meso thi
Metriocnemus spp	Metrind	Metrind	n/a	n/a	Metrind	n/a
Micropsectra spp	Micpind	Micpind	*Micropsectra bidentata* *Micropsectra insignilobus* *Micropsectra radialis*	*Micropsectra atrofasciata* MICRPS	Micpind	*Micropsectra spp*
Microtendipes spp	Mictind	Mictind	*Microtendipes* *Microtendipes II*	*Microtendipes* MICRO	n/a	Mictind
Monodiamesa	Mondind	Mondind	n/a	n/a	Mondind	n/a
Nanocladius spp	Nanoind	Nanoind	*Nanocladius*	*Nanocladius* NANO	n/a	n/a
Nilothauma	Niloind	Niloind	n/a	n/a	n/a	n/a
Omisus	Omisind	n/a	*Omisus*	n/a	n/a	n/a
Pagastiella	Pagaind	Pagaind	*Pagastiella*	*Pagastiella* PAGA	n/a	Pagaind
Parachironomus spp	Parcind	Parcind	*Parachironomus*	n/a	n/a	n/a
Paracladius	Parlind	Parlind	*Paracladius*	n/a	Parlind	*Paracladius*
Paracladopelma	Paraind	n/a	*Paracladopelma*	n/a	n/a	n/a
Paracricotopus	Pacrind	n/a	*Paracricotopus*	n/a	n/a	n/a
Parakiefferiella spp	Parkind	Park nig ParkindB Park tri	*Parakiefferiella*	*Parakiefferiella cf sp B* (Walker 1988) PAKB *Parakiefferiella* (Fig 367 in O&R) PAK367 *Parakiefferiella spp including nigra* PAKSPP	Park nig ParkindB Park tri	Pbat-spB Para nig *Parakiefferiella fennica*

	This study	Barley et al. 2006	Larocque et al. 2006	Wilson and Gajewski 2004	Fortin [3] & Gajewski et al. 2005	Porinchu et al. 2009
Paralimnophyes	Palmind	n/a	*Paralimnophyes*	n/a	n/a	n/a
Parametriocnemus/Paraphaenocladius spp	Pare&P	Pare&P	*Paraphaenocladius*	n/a	Pare&P	Parametr
Parasmittia	Parsind	n/a	*Parasmittia*	n/a	n/a	Parasmittia
Paratendipes spp	Patdind	Patdind	n/a	n/a	n/a	n/a
Pentaneurini-other	trpenta	trpenta	Pentaneurini	Pentaneurini	trpenta	Pentaneurini
Phaenopsectra spp	Phaeind	Phae fla	*Phaenopsectra*	n/a	n/a	n/a
Polypedilum spp	Polyind	Polyind	*Polypedilum* *Polypedilum III C* *Polypedilum type II*	*Polypedilum*	n/a	Polyind
Potthastia	Pottind	Pottind	n/a	n/a	Pottind	n/a
Procladius	Procind	Procind	*Procladius*	Procladius PROC	Procind	*Procladius*
Propsilocerus spp	Propind	n/a	n/a	n/a	Propind	n/a
Protanytpus	Protind	Protind	*Protanypus*	n/a	Protind	*Protanypus*
Psectrocladius (Allopsectrocladius/Mesopsectrocladius) spp	PsecAMe	PsecindA	Allopsectrocladius	*Psectrocladius* (Allo/Mesopsectrocladius) ALLOMES	n/a	mesopsectrocladius
Psectrocladius (Monopsectrocladius) spp	PsecMon	PsecindS PsecindM	Psectrocladius septen	*Psectrocladius* (Fig 9 61 D in Wiederholm) PSECTD	n/a	*Psectrocladius septen*
Psectrocladius (Psectrocladius) spp	PsecPse	PsecindE	Psectro Sordidell	*Psectrocladius* (Fig 9 61 E/F in Wiederholm) PSECTEF	PsecindE	Psectro Sordidell
Pseudochironomus	Pseuind	Pseuind	n/a	n/a	n/a	n/a
Pseudodiamesa	Psedind	Psedind	*Pseudodiamesa*	n/a	Psedind	*Pseudodiamesa*
Pseudosmittia/Smittia spp	Pses&S	Pses&S	*Smittia*	n/a	Pses&S	*Pseudosmittia*
Rheocricotopus spp	Rheoind	Rheoind	n/a	n/a	n/a	Rheocric
Sergentia spp	Sergind	Sergind	*Sergentia*	*Sergentia* (SERG)	Sergind	Sergind
Stempellina	Stemind	stemind	n/a	n/a	n/a	n/a
Stempellinella/Zavrelia spp	Step&Z	Step&Z	*Stempellinella*	n/a	n/a	StemZav
Stictochironomus spp	Sticind	Sticind	*Stictochironomus*	n/a	Sticind	Sticind
Symposiocladius lignicola	Symp lig	Symp lig	n/a	n/a	n/a	n/a
Synorthocladius	Synoind	Synoind	n/a	n/a	n/a	n/a
Tanypus	Tanpind	Tanpind		n/a	n/a	n/a
Tanytarsina-other	trtanyt	trtanyt Tany chi Corynamb Rhetind Stemind	*Tanytarsus* without *Tanytarsus* with *Tanytarsus chinyensis* *Tanytarsus sp# B* *Tanytarsus sp# C* *Tanytarsus lugens* *Tanytarsus pallidicornis* *Paratanytarsus*	*Tanytarsina* TANYT *Tanytarsus sp C* TANYC *Tanytarsus lugens* group TANLU *T lugens/C oliveri type* TANLUCO *Tanytarsus pallidicornis* type TANYP *Paratanytarsus* PARAT	trtanyt	*Tanytarsus spp* *Tanytarsus lugens* *Tanytarsus pallidicornis* *Paratanytarsus*

	This study	**Barley et al. 2006**	**Larocque et al. 2006**	**Wilson and Gajewski 2004**	**Fortin [3] & Gajewski et al. 2005**	**Porinchu et al. 2009**
Thienemannimyia spp	Thienem	n/a	Thienemany	n/a	n/a	*Thienemannimyia type*
		n/a	* Telopelopia	n/a	n/a	
Tribelos	Tribind	Tribind	n/a	n/a	n/a	n/a
Unknown chironomidae	fchiron	fchiron		** Psectrocladius spp PSECT	fchiron	
				Orthocladiinae (unknown) ORTHO		
Xenochironomus	Xenoind	Xenoind	n/a	n/a	n/a	n/a
Zalutschia spp	Zaluind	Zaluind1 Zaluind3	*Zalutschia lingulata pauca*	n/a	*ZalA&Ba* *ZalB&Ba* *ZalB&Br*	Zalutschia sp A Zalutschia sp B
Zalutschia zalutschicola	Zaluzal	Zaluind2	*Zalutschia zalutschicola*	n/a	n/a	*Zalutschia zalutschicola*
Zavrelimyia spp	Zavrind	n/a	*Zavrelimyia*	n/a	n/a	n/a

Appendix 4:

Lake WB02 chironomid head capsule raw counts

Depth (cm)	Cal yr (1997)	Chirind anth	Sergind	Sticind	Cory amb	Cory oli	Micpind rad	Micpind ins	Micpind rad/ins	Ptanind aus w
0 25	2	0	0	0	0	0	0	0	0	0
0 75	5	0	4 5	1 5	0	0	0	15	0	0
1 25	10	0	1	1	0	0	0	14 5	0	0
1 75	16	0	0	6	0	0	0	15 5	0	0
2 25	22	0	0	3	0	0	0	13 5	0	0
2 75	30	0	0	2	0	0	0	16	0	0
3 25	39	0	0	4 5	0	0	0	14	0	0
3 75	48	0	1 5	2	0	0	1	9 5	0	0
4 25	58	0	0	7	0	0	0	18	0	0
4 75	70	0	0	6	0	0	0	4	0	0
5 5	88	0	2	8	0	0	0	4	0	0
10 5	258	0	2	10	0	0	0	4 5	0	0
15 5	499	0	0	8 5	0	0	0	0	0	0
20 5	799	0	0	27	0	0	0	7	0	0
25 5	1146	0	0	18 5	0	0	0	1	0	0
30 5	1530	0	0	0	0	0	0	0	0	0
35 5	1940	0	0	4	0	0	0	0	0	0
40 5	2368	0	0	40	0	1	0	3	0	0
45	2761	0	1	17	0	0	0	0	0	0
45 5	2805	0	0	42 5	0	0	1	2	0	0
49	3112	0	1	34 5	0	0	0	4	0	0
55	3633	0	0	22 5	0	0	0	5	0	0
60	4055	0	1	17	0	0	0	3	0	0
65	4462	0	12	4	0	0	0	3	0	0
70	4848	0	1	5	0	0	0	1	0	0
75	5210	0 5	4	25 5	0	0	0	16	0	0
80	5545	0	1 5	0	0	0	0	10	0	0
85	5852	0	0	0	0	0	0	0	0	0
89	6075	0	4	0	0	1	0	31	0	0
90	6128	3	5 5	10	0	0	0	40 5	0	0
92	6230	9	2	9 5	0	1	0	14 5	0	0
95	6374	0	0	2	0	0	0	1	0	0
100	6590	0	1	0	0	0	0	4	0	0
105	6777	0	1 5	2	0	0	0	33 5	0	0
110	6938	0	6	2	0	1	1	29	0	0
114 5	7062	0	7 5	3	0	0	0	66	0	4
115	7075	0	1	1	0	0	4	32 5	0	0
119 5	7181	0	0	4	0	0	0	16	0	1
120	7192	0	3	2	0	0	1	40	0	1
124 5	7283	1	5	2	0	1	0	29 5	0	7
125 00	7293	0	1 5	0	0	0	0	8	0	1
129 5	7375	0	0	1	0	0	1	7	0	5
130	7384	0	2	0	0	0	0	23	0	12
134 5	7462	1	1	1	0	0	1	11	0	1
135	7471	3	8	1	0	0	0	57	0	1
139 5	7551	2	2	0	0	0	0	3	0	1
144 5	7649	0	22	0	104 5	0	0	68	0	1
149 5	7766	0	9 5	0	46	0	2	50	0	0
154 5	7910	0	0	0	24	0	0	7	0	1
159 5	8091	2	3 5	2	0	0	6	10 5	0	7
164 5	8321	0	0	0	0	0	0	27	0	1

Depth (cm)	Ptanınd aus no	Ptanınd aus/pen	Ptanınd pen no	Ptanınd pen w	Tanyınd lug w	Tanyınd lug no	Tanyınd lug/mend	Tanyınd men no
0 25	0	0	0	0	0	0	0	0
0 75	0	2	0	0	0	0	0	0
1 25	0	0 5	0	0	0	0	0	0
1 75	0	0 5	0	0	0	0	0	0
2 25	0	3	0	0	0	0	0	0
2 75	0	0	0	0	0	0	0	0
3 25	0	1	0	0	0	0	0	0
3 75	0	3	0	0	0	0	0	0
4 25	0	0	0	0	0	0	0	0
4 75	0	0	0	0	0	1	0	0
5 5	0	0	0	0	0	0	0	0
10 5	1 5	1	0	0	0	0	0	0
15 5	0	0	0	0	0	0	0	0
20 5	0	2 5	0	0	0	0	0	0
25 5	0	0	0	0	0	0	0	0
30 5	0	0	0	0	0	0	0	0
35 5	0	0	0	0	0	0	0	0
40 5	0	15 5	0	0	0	0	0	0
45	3	2 5	0	0	0	3	0	0
45 5	0	26	0	0	0	0	0	0
49	1	23 5	0	0	0	0	0	0
55	2	3 5	0	0	0	0	1	0
60	6	4	0	0	0	0	0	0
65	7	7	0	0	0	0	0	0
70	4	3	1	0	0	0 5	0	0
75	2	10	0	0	0	0	0	0
80	9 5	8 5	0	0	0	0	0	0
85	0	1	0	0	0	0	0	0
89	0	47 5	0	0	0	0	3	0
90	43 5	9 5	0	0	1	7	2	0
92	0	8	0	1	0	0	0	0
95	0	0	0	0	0	0	0	0
100	0	2	0	0	0	0	0	0
105	16 5	17	0	0	0	7 5	0	0
110	19	20	0	0	5	1	1	0
114 5	83	33	0	0	8	30	12	0
115	29 5	8	0	0	1	10	0	0
119 5	4	0	1	0	3	2	3	0
120	23	7	0	0	3	13	3	0
124 5	25	29	0	0	5	16	5 5	0
125 00	3	9	0	0	2	4	4	9
129 5	14	6	3	0	2	7	1	0
130	28	8	0	0	19	24	7	0
134 5	5	15	0	0	1	1	2	0
135	36	22 5	0	0	26	39	20 5	0
139 5	5	2	0	0	1	4	1 5	0
144 5	63	21	0	0	3	22	15	0
149 5	25 5	20	2	0	2	8	4	0
154 5	2	5	0	0	0	1	1	0
159 5	20 5	27	0	1	11	8	9	2
164 5	20 5	11	0	0	15	34	9 5	1

Depth (cm)	Tanyind men w	trtany t	Diamind	Protind	Psedind	Mondind	Abisind	Bril& E	Cory&T	CricoB	Cric& O	Euki &T
0 25	0	0	0	0	0	0	0	0	0	0	0	0
0 75	0	7	0	0 5	0	0	50	0	1	0	2	0
1 25	0	8 5	0	1 5	0	0	24	0	0	0	0	0
1 75	0	4	0	0	2 5	0	25	0	0	0	0	0
2 25	0	4	0	0	0 5	0	23 5	0	0	0	0	0
2 75	0	4	0	0 5	1	0	28	0	0	0	0	0 5
3 25	0	1 5	0	0 5	3	0	46 5	0	1	0	1	0
3 75	0	3	0	1	1	0	28	0	0	0	1	0 5
4 25	0	4	0	3 5	0 5	0	49	0	0	0	2	0
4 75	0	2	0	1 5	1	0	25	0	1	0	1	0
5 5	0	1	0	0	1 5	0	7 5	0	0	0	0	0
10 5	0	2 5	0	0	0 5	0	15 5	0	0	0	0	0
15 5	0	1	0	0	2	0	4	0	0	0	0	0
20 5	0	4	0	0	0	0	2 5	0	0	0	0	0
25 5	0	5	0	4 5	0	0	0	0	0	0	0	0
30 5	0	0	0	0	0	0	0	0	0	0	0	0
35 5	0	3	0	0	0	0	0	0	0	0	0	0
40 5	0	4	0	0	0	0	0	0	0	0	0	0
45	0	1	0	0	0	0	1 5	0	0	0	0	0
45 5	0	8 5	0	0	0 5	0	0 5	0	0	0	0	1
49	0	5 5	0	1	0	0	0	0	1	0	0	0
55	0	5	0	1	0	0	0 5	0	0	0	0	0
60	0	3	0	0	0	0	0 5	0	0	0	0	0
65	0	5	0	0	0	0	0	0	0	0	0	1
70	0	4	0	0	0	0	0	0	0	0	0	0
75	0	3	0	0	0	0	5	0	0	0	2	3 5
80	0	4 5	0	0	0	0	5	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	1 5
89	0	14	0	0	0	0	15	0	0	0	0 5	0
90	0	12 5	0	0 5	0	0 5	0	0	0	0	0	0
92	0	2 5	0	1 5	0	0	1	0	0	0	3	1
95	0	0 5	0	0	0	0	0	0	0	0	1	0 5
100	0	1	0	0	0	0	0	0	1	0	0 5	1
105	0	13 5	0	0	0	1	0	0	0	0 5	0	0 5
110	0	12 5	0	0	0	0	0	0	0	0	0	0
114 5	0	43 5	1	0	0	1	0	0	0	0	0	0
115	0	14	1	0	0	0	0	0	0	0	0	1
119 5	1	7	1	0	0	1 5	0	0	0	0	0	0
120	0	17 5	0 5	3	0	3	0	0	0	0	0	1 5
124 5	0	15 5	0	0	0	0	0	0	0	1	0	2 5
125 00	1	5	0	0	0	0	0	0	0	0	0	0
129 5	0	3	0	0	0	0	0	0	0	0	0	2
130	0	22	0	0	0	0	0	0	0	0	0	0
134 5	0	5 5	1	0	0	0	0	0	0	0	0	0
135	0	36 5	1	1	0	2 5	0	0	0	0 5	1	2
139 5	0	2	1	0	0	0	0	0	0	0	1	0
144 5	0	28 5	0	1 5	0	0	0	0	0	0	0	0 5
149 5	0	16	0	0	0	0	0	0	1	0	0	1
154 5	0	3	1	0	0	0	0	0	0	0	0	0
159 5	1	44	1 5	1	0	1	0	0	0	0	1	0
164 5	1	14 5	1	0	0	0	0	0	0	0	0 5	0

Depth (cm)	Heteınd mae 1d	Heteınd mae 1p	Heteınd mae 2d	Heteınd mae 2p	Heteınd mar	Heteınd sub	Heteınd grı	Hydr&O	Lımnı nd
0 25	0	0	0	0	0	0	0	0	0
0 75	3 5	2 5	1	1 5	0	0	0	0	0
1 25	4	2	0	0	0	0	0	0	0
1 75	3	1	0	0	0	0	0	0	0
2 25	3	2	0 5	0	0	0	0	0	0
2 75	3	1	0	0	0	0	0	0	0
3 25	2	0	0	0	0	0	0	0	0
3 75	5	0	0	0	0	0	0	0	0
4 25	4 5	0	0	0	0	0	2	0	0
4 75	4	0 5	0	0	0	0	0	0	0
5 5	0	0 5	0	0	0	0	0	0	0
10 5	3	1	0	0	0	1	0	0	0
15 5	3	1	0	0	0	0	0	0	0
20 5	8	4	0	0	0	1	0	0	0
25 5	11	15	1 5	0	0	2	0	0	0
30 5	0	0	0	0	0	0	0	0	0
35 5	0 5	2	0	0	0	0	0	0	0
40 5	46	3	0 5	2 5	0	3	0 5	0	0
45	5	3 5	1	0	0	0	1	0	0
45 5	70 5	1	5	0	0	2 5	0	0	0
49	26	3	1 5	1 5	0	0	2	0	0
55	12 5	3 5	0 5	0	0	1 5	0	0	0
60	22	6 5	4	0	0	1	0	0	0
65	3	4	3	0	0	0 5	0	0	0
70	8	1	0 5	0	0	1	0	0	0
75	15 5	2	1 5	1	0	1 5	0 5	0	0
80	3	0 5	0	0	0	0	0	0	1
85	0	0	0	0	0	0	0	0	0
89	12	0	2 5	0	0	0	0 5	0	0
90	11	0	5 5	0	0	0	0	0	0
92	6	0	1	0	0	0	0	0	0
95	1	0	0	0	0	0	0	0	0
100	2 5	0 5	0	0	0	0	0	0	1
105	12	1 5	0	1	0	1	0	0	0
110	4	3 5	1	0	0	1	0	0	0
114 5	4 5	3	0	0 5	0	1	0	0	0
115	5 5	0	0	0	0	0	0	0	0
119 5	0	2	3	0	0	0 5	0	0	0
120	7 5	0 5	0	0	0	2	0	0	0
124 5	9	2	4	0	0	3	0	0	0 5
125 00	3	0 5	0	0	0	1 5	0	0	0
129 5	2	0	0	0	0	0	0	0	0
130	2 5	1 5	0	0	0	0	0	0	0
134 5	5	0 5	0	0	0	0 5	0	0	0
135	9 5	3	0	0 5	0	2 5	0	0	0
139 5	1 5	0	0	0	0	0	0	0	0
144 5	5	2	0 5	0 5	0	0	0	0	0
149 5	2 5	0 5	0 5	0	0	0	0	0	0
154 5	0	0 5	0	0	0	0	0	0	0
159 5	6	4	1	0	0	0 5	0	0	1
164 5	3	1 5	0	0	0	0	0	0	0

Depth (cm)	Mescind	Metrind eury	Parlind	Parkind nig	Parkind spB	Parkind tri	PsecPse	PsecAMe	Pses&S	Zaluind spB	Tanyp-UK
0 25	0	0	0	0	0	0	0	0	0	0	0
0 75	0	0	13	2 5	0	0	0	0	0	4 5	0 5
1 25	0	0	1 5	5 5	0	0	0	0	0	1 5	2
1 75	0	0	10 5	5 5	0	0	0 5	0	0	1	0
2 25	0	0	6	7 5	0	0	1 5	0	2	3	2
2 75	0	1	8 5	3	0	0	0	0	0	2	0
3 25	0	0	8	4 5	0	0	0 5	0	0	4 5	1
3 75	0	0	5	3	0	0	0	0	0	3 5	0
4 25	0	0	8 5	1	0	0	0	0	0	2 5	0
4 75	0	0	2 5	2	0	0	0	0	0	1 5	0
5 5	0	0	2	1 5	0	0	0	0	0	0 5	0
10 5	0	0	16	3 5	0	0	0 5	0	0	0	0
15 5	0	0	10 5	0	0	0	0	0	0	1	0
20 5	0	0	15	0	0	0	0	0	0	0	0
25 5	1	0	37 5	0 5	0	0	0	0	0	2	1
30 5	0	0	0 5	0	0	0	0	0	0	0	0
35 5	0	0	4	0	0	0	0	0	0	0	0
40 5	0	0	97 5	0	0	0	0 5	0	0	10	3
45	0	0	10 5	0	0	0	0	0	0	2 5	0
45 5	1	0	70	0	0	0	0	0	0	7 5	4
49	0 5	0	42 5	0 5	1	0	0	0	0	2	5
55	0	0	32	0	0	0	0	0	0	2	6
60	0	0	22	0	0	0	0	0	0	7	3
65	0	0	13 5	0	0	0	0	0	0	0 5	3
70	3	0	20	0	0	0	0	0	0	0	0
75	4 5	0	62	1	0	0	0 5	0	0	4	5
80	0	0	13 5	0	0	1	0	0	0	0	5
85	0	0	1	0	0	0	0	0	0	0	0
89	1 5	0	32	0	0	0	8 5	0	0	2	22
90	1 5	0	48 5	0	0	0	3	0	0	0	1
92	1	0	12	0	0	0	0 5	0	0	0 5	1
95	0	0	1 5	0	0	0	0	0	0	0	0
100	0	0	3	0	0	0	1 5	0	0	0	3
105	0	0	55	0	0	0	10	0	0	0	12
110	0	0	23	0	0	1	16	0	0	0 5	5
114 5	0	0	106 5	0	0	0	22 5	0	0	1	13
115	0	0	41	0	0	1	4	0	0	0	8
119 5	0	0	12	0	0	0	7	0	0	0	0
120	0	0	43 5	0	0	0	10	0	0	0	3
124 5	0	0	66 5	0	0	0	12	0	0	2	24
125 00	0	0	20 5	0	0	0	6 5	0	0	0	7
129 5	0	0	4 5	0	0	0	1 5	0	0	0	4
130	0	0	8 5	0	0	0	11	0	0	0	12
134 5	0	0	23	0	0	0	0	0	0	0	9
135	0	0	177	0	0	0	6	0	0	0	22
139 5	0	0	28	0	0	0	0	0	0	0	5
144 5	0	0	47 5	0	0	0	6 5	0	0	0	42
149 5	0	0	14	0	0	0	0	0	0	0	33
154 5	0	0	3 5	0	0	0	0	0	0	0	0
159 5	0 5	0	147 5	0	0	0	13 5	0	0	0	21
164 5	0	0	48 5	0	0	0	8	0	0	0	12

Depth (cm)	Procind	Tanpind	UK	TOTAL HC	Total CC	HC/CCwet sed	HC/g(dry weight)
0 25	0	0	0	0	2	0	0
0 75	0	0	0	112 5	1	113	169
1 25	0	0	0	67 5	2	34	70
1 75	0	0	0	75	4	19	50
2 25	0	0	0	75	4	19	47
2 75	0	0	0	70 5	4	18	42
3 25	0	0	0	93 5	4	23	56
3 75	0	0	0	68	2	34	90
4 25	0	0	0	102 5	3	34	75
4 75	0	0	0	53	2	27	48
5 5	0	0	0	28 5	2	14	19
10 5	0	0	0 5	63	3	21	25
15 5	0	0	0	31	2 5	12	16
20 5	0	0	1	72	3 25	22	25
25 5	1	0	0	101 5	3 5	29	28
30 5	0	0	0	0 5	3	0	0
35 5	0	0	0	13 5	2	7	7
40 5	5	0	0	235	6	39	45
45	1	0	1	54 5	3 5	16	18
45 5	5	0	0 5	249	6	42	51
49	2	0	0	159	6	27	33
55	1	0	0 5	100	4 25	24	31
60	2	0	0	102	2	51	61
65	2	0	0	68 5	4	17	22
70	0	0	0	53	2	27	30
75	2	0	0	172 5	6	29	34
80	0	0	1	64	2 5	26	23
85	0	0	0	3 5	3	1	1
89	3	0	0	200	1	200	378
90	1	0	5	212	2	106	139
92	0	0	0	76	1	76	65
95	0	0	0 5	8	7	1	1
100	0	0	2	24	4 5	5	4
105	11	0	0	197	2	99	142
110	20	0	0	172 5	0 6	288	414
114 5	28	0	0	472	2	236	488
115	6	0	0	168 5	0 6	281	342
119 5	2	0	0 5	71 5	2	36	42
120	12	0	0	200	2	100	88
124 5	9	0	1	278	2	139	161
125 00	4	0	0	90 5	0 6	151	186
129 5	8	0	0	72	2	36	31
130	17	0	2	199 5	2	100	87
134 5	4	0	1 5	90	3	30	25
135	25	0	3 5	507 5	2	254	256
139 5	8	0	0	68	2	34	33
144 5	20	0	2	476	2	238	321
149 5	11	0	2	250 5	2	125	178
154 5	3	0	0	52	0 5	104	145
159 5	24	0	2	380	2	190	201
164 5	18	0	0	227	2	114	157

Taxa code for Appendix 4

Chirind anth	*Chironomus anthracinus* -type
Sergind	*Sergentia* spp.
Sticind	*Stictochironomus* spp
Cory amb	*Corynocera ambigua*-type
Cory oli	*Corynocera oliveri*-type
Micpind rad	*Micropsectra radialis-type*
Micpind ins	*Micropsectra insignilobus-type*
Ptanind aus w	*Paratanytarsus austriacus*-type *with mandibles*
Ptanind aus no	*Paratanytarsus austriacus*-type without mandibles
Ptanind pen w	*Paratanytarsus penicillatus*-type with mandibles
Ptanind pen no	*Paratanytarsus penicillatus*-type without mandibles
Tanyind lug w	*Tanytarsus lugens*-type with mandibles
Tanyind lug no	*Tanytarsus lugens*-type without mandibles
Tanyind men no	*Tanytarsus lugens*-type without mandibles
Tanyind men w	*Tanytarsus lugens*-type with mandibles
trtanyt	Tanytarsina-other
Diamind	*Diamesa* spp.
Protind	*Protanypus*
Psedind	*Pseudodiamesa*
Mondind	*Monodiamesa*
Abisind	*Abiskomyia*
Bril&E	*Brillia/Euryhapsis* spp
Cory&T	*Corynoneura/Thienemanniella* spp
CricoB	*Cricotopus* spB
Cric&O	*Cricotopus/Orthocladius* spp
Euki&T	*Eukiefffer*i*ella/Tvetenia* spp.
Heteind mae 1d	*Heterotrissocladius maeaeri-t*ype1 dark
Heteind mae 1p	*Heterotrissocladius maeaeri-t*ype1 pale
Heteind mae 2d	*Heterotrissocladius maeaeri-t*ype2 dark
Heteind mae 2p	*Heterotrissocladius maeaeri-t*ype2 pale
Heteind mar	*Heterotrissocladius marcidius*-type
Heteind sub	*Heterotrissocladius subpilosus*-type
Heteind gri	*Heterotrissocladius grimshawi*-type
Hydr&O	*Hydrobaenus/Oliveridia* sp
Limnind	*Limnophyes*
Mescind	*Mesocricotopus*
Metrind eur	*Metriocnemus eurynotus*-type
Parlind	*Paracladius*
Parkind nig	*Parakiefferiella nigra*-type
Parkind spB	*Parakiefferiella* spB
Parkind tri	*Parakiefferiella triquetra*-type
PsecPse	*Psectrocladius (Psectrocladius)* spp
PsecAMe	*Psectrocladius (Allopsectrocladius/Mesopsectrocladius)* spp
Pses&S	*Pseudosmittia/Smittia* spp
Zaluind spB	*Zalutschia* spp B
Tanyp-UK	Tanypodinae-UK
Procind	*Procladius*
Tanpind	*Tanypus*

Appendix 5:

Lake KR02 chironomid head capsule raw counts

Cal ka BP (2000)	CC	Start depth (cm)	*Chironomus anthracinus-type*	*Sergentia*	*Stictochironomus*	*Corynocera ambigua-type*	*Corynocera oliveri-type*	*Cladotanytarsus mancus-type*	*Micropsectra radialis-type*
0 004039	0 5	2 5	1	0	0	0	0	0	0
0 005047	2 5	3	3	11	1	0	0	0	0
0 007025	5	4	5 5	12	0	0	0	0	0
0 010156	4 5	5	1	9 5	0	0	0	0	0
0 01725	1 5	6	1 5	10	0	0	1	0	0
0 019997	2 5	7	1	7 5	2	0	0	0	0
0 024155	2 5	8	0	7 5	0	0	1	0	0
0 028522	3 5	9	0	8	0	0	0	0	0
0 0433	7	10	1	8 5	0	0	0	0	0
0 050833	6 5	11	1	9 5	0	0	1	0	0
0 058367	7	12	2	8 5	0	0	0	0	0
0 065902	7	13	3	16	0	0	0	0	0
0 073098	9	14	1	22	0	0	2	0	0
0 080292	4	15	0	12	0	0	2	0	0
0 089662	9	16	1	24 5	1	0	1	0	0
0 099031	5	17	0	12	0	0	1	0	0
0 112918	7 5	18	2	27	2	0	3	0	0
0 126804	4 5	19	3	21	0	0	2	0	0
0 14497	6	20	1	10	0	1	0	0	0
0 323585	3	25	1	9	0	0	0	0	0
0 52411	6	30	3	8	1	0	0	0	0
0 724635	5	35	0	18	3	0	0	0	0
0 90089	5 5	40	2	4	3	0	0	0	0
1 020585	7	45	4	21 5	1	0	0	0	0
1 14028	7	50	6	13 5	2	0	0	0	0
1 26	3 5	55	3	9	9	0	3	2	0
1 379697	2	60	3 5	8	1 5	0	0	0	0
1 499394	5	65	6	15	0	0	2	0	0
1 619091	4	70	2	18 5	0	0	182 5	0	0
1 71031	5	75	4	4	1 5	0	0	0	0
1 789325	6	80	3 5	18	0	0	1	0	0
1 868339	5	85	5	9 5	0	0	1	0	0
1 947354	6	90	5 5	13 5	2	0	1	0	0
2 026369	5	95	5	17 5	7	0	0	0	0
2 105383	8 5	100	7	12	4	0	0	0	0
2 184398	3	105	1	9 5	0	0	0	0	0
2 263412	4 5	110	5	12 5	2	0	0	0	1
2 342427	5	115	7 5	4 5	3	0	1	0	0
2 421442	7	120	12 5	29 5	3 5	0	0	0	0
2 500456	4	125	3	4 5	0 5	0	0	0	0
2 579471	4	130	5	9 5	2	0	0	0	0
2 658485	6	135	9	15 5	1 5	0	2	0	0
2 7375	7	140	2 5	3	0	0	0	0	0
2 816515	6	145	4	10 5	2	0	1	0	0
2 895529	6	150	18	6	0	0	6	0	0
2 974544	3	155	3	6	1	0	0	0	0
3 053558	2 5	160	2	8 5	0	0	0	0	0
3 132573	5	165	2	3	1	0	1	0	0
3 211588	6	170	4	2	0	0	0	0	0
3 290602	6	175	3 5	2	1	0	0	0	0
3 369617	6	180	0 5	0 5	0	0	0	0	0
3 49604	2	188	4	1	0	0	0	0	0
3 575055	5 5	193	7 5	2 5	0 5	0	1	0	0
3 654069	6	198	8 5	4	1 5	0	0	0	0
3 733084	7	203	14	1	1	0	0	0	0
3 812099	2	208	7	1 5	0	0	0	0	0
3 964403	2	213	2 5	1	2	0	0	0	0
4 124851	5	218	1	1	0	0	0	0	0
4 285299	6	223	0	4 5	1 5	0	0	0	0

Start depth (cm)	*Micropsectra insignilobus-type*	*Paratanytarsus austriacus-type w mandibles*	*Paratanytarsus austiacus/penicillatus-type*	*Paratanytarsus penicillatus-type w mandibles*	*Tanytarsus lugens-type w mandibles*	*Tanytarsus lugens/mendax-type*	*Tanytarsus mendax-type w mandibles*	*Tanytarsina-other*
2 5	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	3	0	0	0	0	0	0	2 5
5	1	0	0	0	0	2	0	0
6	3	0	1	0	0	0	0	4
7	1	0	2 5	0	0	0	0	1 5
8	1	0	2	0	0	0	0	0
9	1	0	1	0	0	0	0	2 5
10	3	0	0	0	0	0	0	2 5
11	0	0	0 5	0	0	0	0	1 5
12	0	0	1	0	0	0	0	0 5
13	2	0	0	1	0	0	0	3
14	6 5	0	4 5	0	0	2	0	5 5
15	1	0	1	0	0	0	0	0
16	8 5	0	3	0	1	0	0	4
17	2	0	3	0	0	0	0	0
18	10	0	0	0	0	0	0	4
19	6	0	0	0	0	0	0	6
20	4	0	3 5	0	0	0	0	2
25	1	0	0	0	0	0	0	0
30	4	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	1 5
40	0	0	1	0	1	0	0	0
45	6	0	2	0	1	0	0	6 5
50	1	0	1	0	1	0	0	2
55	2	1	1	0	0	0	0	5
60	2	0	2	0	0	2	0	3 5
65	2	0	0	0	0	6	0	12 5
70	0	0	3	0	3	12	0	18 5
75	0	0	0	0	0	9	0	3
80	4 5	0	0	0	0	4	0	7
85	1	0	0	0	4	0	0	9
90	0	0	0	0	0	0	0	0
95	6	0	4	0	0	0	0	4 5
100	3	0	3	0	0	0	0	0
105	0	0	1	0	0	0	0	1
110	0	0	1	0	0	0	0	1
115	1	0	0 5	0	0	0	0	1
120	3	0	2	0	0	0	0	3
125	2	0	0	0	0	0	0	2
130	2	0	2	0	0	1	0	1
135	4	0	2	0	0	0 5	0	3
140	2	0	0	0	0	0	0	1
145	0	0	2	0	0	0	0	2 5
150	1	0	7 5	0	0	0	0	7 5
155	3	0	1	0	0	2	0	2
160	0	0	1	0	0	0	0	2 5
165	0	0	2	0	0	0	0	0
170	0	0	0	0	0	0	0	0
175	1	0	5 5	0	0	0	0	4
180	0	0	0	0	0	0	0	0
188	1	0	0	0	0	0	0	1 5
193	6 5	0	6 5	0	0	1	0	4
198	7	0	15	0	0	2	0	9 5
203	3	2	4 5	0	0	0	0	5 5
208	1	0	1	0	0	0	0	3 5
213	0	0	2	0	0	0	0	1 5
218	0	0	0	0	0	0	0	0
223	0	0	0	0	0	0	0	0 5

Start depth (cm)	*Tanyarsina pallidicornis-type*	*Protanypus*	*Pseudodiamesa*	*Monodiamesa*	*Abiskomyia*	*Brillia/Euryhapsis spp*	*Corynoneura/Thienemanniella spp*	*Corynoneura Arctica*
2 5	0	0	0	0	0	0	0	0
3	0	0	0	0	0 5	0	0	0
4	0	0	0 5	0	3	0	0	0
5	0	0	0	0	2	0	0	0
6	0	0	0	0	3 5	0	0	0
7	0	0	0	0	4	0	0	0
8	0	0	0	0	3 5	0	0	0
9	0	0	0	0	7 5	0	0	0
10	0	0	1	0	8	0	0	0
11	0	0 5	0	0	9	0	3	0
12	0	0	0	0	12	0	0	0
13	0	0	3 5	0	15	0	0	0
14	0	0	0 5	0	28	0	1	0
15	0	0	0 5	0	13 5	0	0	0
16	0	0	1 5	0	30 5	0	0	0
17	0	0	0 5	0	13 5	0	0	0
18	0	0	0	0	29 5	0	0	0
19	0	0	0 5	0	23	0	0	0
20	0	0	0	0	18	0	0	0
25	0	0	0	0	6 5	0	0	0
30	0	0	0 5	0	10	0	0	0
35	0	0	0	0	15 5	0	0	0
40	0	1	0	0	3 5	0	0	0
45	0	0	0	0	9 5	0	0	0
50	0	0	0	0	1 5	0	0	0
55	0	0	0	0	0 5	0	0	0
60	0	0	0	0	3	0	0	0
65	0	0 5	0	0	2	0	0	0
70	0	0	0	0	0	0	0	0
75	0	0	3	0	2	0	0	0
80	0	0	1 5	0	14	0	0	0
85	0	0	1	0	13 5	0	0	0
90	0	0	1 5	0	1 5	0	0	0
95	0	0 5	0 5	0	40	0	0	0
100	0	1	0	0	7 5	0	0	0
105	0	0	0	0	0	0	0	0
110	0	0	0 5	0	1	0	0	1
115	0	0	0	0	0 5	0	0	0
120	0	0	1 5	0	3 5	0	0	0
125	0	0	1 5	0	0	0	0	0
130	0	0 5	2	0	4 5	0	0	0
135	0	0	0 5	0	5	0	0	0
140	0	0	1	0	0	0	0	0
145	0	0 5	1	0	2 5	0	0	0
150	0	0	2 5	0	5 5	0	0	0
155	0	0	0	0	3	0	0	0
160	0	1	5	0	0	0	0	0
165	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0
175	0	0	1	0	1	0	0	2
180	0	0	0	0	0	0	0	0
188	1	0	0	0	4 5	0	0	0
193	0	0	2 5	0	18	0	0	0
198	0	0	5	0	28 5	0	0	0
203	0	0	3	0	5 5	0	0	0
208	0	0	0	0	22	0	0	0
213	0	0	0	0	18 5	0	0	0
218	0	0	0	0	6 5	0	0	0
223	0	0	0	0	31 5	0	0	0

Start depth (cm)	*Cricotopus/Orthocladius spp*	*Orthocladius type S*	*Ortho 1*	*Ortho T1*	*Cricotopus MC*	*Cricotopus 1*	*Cricotopus 2*	Cricotopus cylindraceus-type
2 5	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0 5	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0 5	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0 5	0	0	0	0	0	0	0
10	0 5	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	1	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	1	0	0	0	0	0	0	0
17	1	0	0	0	0	0	0	0
18	1 5	0	0	0	0	0	0	0
19	2 5	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0 5	0	0
45	1	0	0	0	0	1 5	0	0
50	0	0	0	0	0	0	0	0
55	0	1	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
65	1	0	0	0	0	0	0	0
70	1	0	0	0	0	0 5	0	0
75	0	0	0	0	0	0	0	0
80	1	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
95	0 5	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0
115	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0
130	1	0	0	0	0	0	0	0
135	1	0	0	0	0	0	0	1 5
140	3	0	0	0	0	0	0	0
145	0	0	0	0	0	0	0	0
150	0 5	0	0	0	0	0	0	0
155	0	0	0	0	0	0	0	0
160	1	0	0	0	0	0	0	0
165	1	0	0	0	0	0	0	0
170	1	0	0	0	0	0	0	0
175	4	0	0	0	0	1	2	0
180	0	0	0	0	0	0	0	0
188	4 5	0	0	0	0	0	0	0
193	0 5	0	0	0	0	2 5	0	0
198	9 5	0	0	0	0	9 5	0	7
203	0	0	0	0	0	16 5	4	0
208	0	0	0	0	0	1	4	0
213	1 5	0	0	0	0	0	0	0 5
218	0	0	0	0	0	0 5	0	0
223	2	0	0	0	1 5	0	0	0

Start depth (cm)	Cricotopus intersectus	Cricotopus laricomalis-type	Cricotopus sylvestris-type	*Eukiefferiella/ Tvetenia spp*	*Heterotrissocladius maeani Type1 dark*	*Heterotrissocladius maeani Type1 pale*	*Heterotrissocladius maeani Type2 dark*	*Heterotrissocladius maeani Type2 pale*
2.5	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0.5	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	1	0	0	0	0
25	0	0	0	0	0	0	0	0
30	0	0.5	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0
40	0	0.5	0	0	0	0	0	0
45	0	0	0	0	0.5	1	4	0.5
50	0	0	0	0	0	0	1.5	0
55	0	1	0	0	0	1.5	0	0
60	0	0	0	0	0	1	0	0
65	0	0	0	0	0.5	0.5	0	0
70	0	0	0	0	0.5	0	1	0
75	0	0	0	0	0	0	0	0
80	0	0.5	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0.5	0	0
100	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0.5	0	0
115	0	0	0	0	0	0	0	0
120	0	1	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0
135	0	1	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0
145	0	0.5	0	0	0.5	0	0	0
150	0	0	0	0	0	0	0	0
155	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0
165	0	1	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0
188	0	0	0	0.5	0	0	0	0
193	0	0	0	0	0	0	0	0
198	0	0.5	0	0	0	0	1.5	0
203	0	0	0	0	0	0	0	0
208	0	1	0	0	0	0	0	0
213	0	0.5	0	0	0	0.5	0	0
218	0	0	0	0	0	0	0	0
223	0	0	0	0	0	0.5	0	0

Start depth (cm)	*Heterotris socladius marcidus*	*Heterotris socladius subpilosis*	*Heterotris socladius grimshawi*	*Hydrobaenus/ Oliveridia spp*	*Limnophyes*	*Mesocricotopus*	*Metriocnemus terrester*	*Metriocnemus eurynotus*
2 5	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	1	0
55	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0
70	0	2	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
95	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0
115	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0
125	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0
135	0	0	0	0	0	0	1	0
140	0	0	0	0	0	0	0	0
145	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
155	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0
165	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0
175	0	0	0	0	1	0	1	0
180	0	0	0	0	0	0	1	0
188	0	0	0	0	0	0	0	0
193	0	0	0	0	0	0	0	0
198	0	0	0	0	0	0	0	0
203	0	0	0	0	0	0	2	0
208	0	0	0	0	0	0	0	0
213	0	0	0	0	0	0	1	0
218	0	0	0	0	0	0	0	0
223	0	0	0	0	0	0	0	0

Start depth (cm)	*Paracladius*	*Parakief feriella nigra*	*Parakief feriella bathophila-type*	*Parakief feriella spB*	*Parakief feriella triquetra type*	*Psectrocladius (Psectrocladius)*	*Pseudosmittia*	*Smittia*	*Zalutsc hia spB*	Tanypo dinae-UK
2 5	3 5	0	0	0	0	0	0	0	0 5	0
3	10 5	0	0	0	0	0	0	0	3 5	0
4	23	0	0	0	0	0	0	0	5	0
5	9	0	0	0	0	0	0	0	4 5	0
6	13 5	0	0	0	0	1	0	0	4 5	0
7	14	0	0	0	0	0	0	0	3 5	0
8	10	0	0	0	0	0	0	0	2	0
9	18	0	0	0	0	0 5	0	0	4 5	1
10	19	0	0	0	0	0	0	0	5	0
11	28 5	0	0	0	0	0	0	0	10 5	0
12	18	0	0	0	0	1 5	0	0	2 5	0
13	21	0	0	0	0	0	0	0	8	0
14	36	0	0	0	0	0 5	0	0	10 5	0
15	20	0	0	0	0	0	0	0	3 5	0
16	38	0	0	0	1	2 5	0	0	10 5	0
17	20 5	0	0	0	0	0	0	0	3	0
18	32 5	0	0	0	0	0	0	0	10	0
19	32	0	0	0	0	0	0	0	6 5	0
20	18 5	0	0	0	0	0	0	0	5	0
25	6	0	0	0	0	0	0	0	0	0
30	15	0 5	0	0	0	0	0	0	3 5	0
35	12 5	0	0	0	0	0	0	0	3	0
40	14 5	0	0	0	0	0	0	0	0 5	0
45	22 5	0	0	0	0	1	0	0	10 5	1
50	11	0	0	0	0	1	0	0	1 5	0
55	14 5	0	0	0	0	1 5	0	0	2 5	0
60	11	0	0	0	0	2	0	0	2 5	2
65	29 5	0	0	0	0	1 5	0	0	1 5	2
70	79 5	0 5	0	0	0	1	0	0	1	2
75	9	0	0	0	0	0	0	0	1 5	0
80	20 5	0	0	0	0	0 5	0	0	2 5	0
85	9	0	0	0	0	0	0	0	1	0
90	19	0	0	0	0	0	0	0	3	0
95	39 5	0	0	0	0	0	0	0	12	0
100	27	0	0	0	0	0	0	0	5 5	0
105	4 5	0	0	0	0	0	0	0	0 5	0
110	21	0	0	0	0	0	0	0	4	0
115	22 5	0	0	0	0	0	0	0	3	2
120	41	0	0	0	0	0	0	0	9 5	0
125	10 5	0	0	0	0	0	0	0	4	0
130	27	0	0	0	0	0	0	0	6	0
135	28	0	0	0	0	0 5	0	0	8	0
140	9 5	0	0	0	0	0	0	0	3 5	0
145	29	0	0	0	0	0 5	0	0	8	0
150	59	0	0	0	0	1 5	0	0	12	0
155	17 5	0	0	0	0	0	0	0	5	0
160	11	0	0	0	0	0	0	0	0	0
165	17 5	0	0	0	0	0	0	0	2 5	0 5
170	8	0	0	0	0	0	0	0	3 5	0
175	42 5	0	0	0	0	0	0	0	10	2
180	5 5	0	0	0	0	0	0	0	1	0
188	24	0	0	0	0	0	0	0	4	1
193	20 5	0	0	0	0	0	0	0	6 5	0
198	29	0	0	0	0	0	0	0	12 5	0
203	17	0	0	0	0	0 5	0	0	5	0
208	11 5	0	0	0	0	0 5	0	0	1	0
213	7	0	0	0	0	0	0	0	1	0
218	2	0	0	0	0	0	0	0	0 5	0
223	5 5	0	0	0	0	1	0	0	3	0

Start depth (cm)	Tanypodinae-UK	*Procladius*	Unknown	Unidentifiable	TOTAL HC	Concentration (HC/CC)
2 5	0	0	0	0	5	10 00
3	0	0	0	2	29 5	11 80
4	0	0	0	1 5	55	11 00
5	0	0	0	0	29	6 44
6	0	0	0	0	43	28 67
7	0	0	0	1 5	37 5	15 00
8	0	0	0	0	27	10 80
9	1	0	1	0	45 5	13 00
10	0	0	0	1 5	49	7 00
11	0	0	0	1 5	65	10 00
12	0	0	1	2	48	6 86
13	0	0	0	0	72 5	10 36
14	0	0	0	2 5	121	13 44
15	0	0	0	0 5	53 5	13 38
16	0	0	1	0	130	14 44
17	0	0	0	0	56 5	11 30
18	0	0	0	1 5	121 5	16 20
19	0	0	0	1	102 5	22 78
20	0	0	0	1 5	64	10 67
25	0	0	0	2	23 5	7 83
30	0	0	0	0 5	46	7 67
35	0	0	0	5 5	53 5	10 70
40	0	0	1	1 5	32 5	5 91
45	1	0	0	4 5	95	13 57
50	0	0	0	1	44	6 29
55	0	0	0	5 5	57 5	16 43
60	2	0	0	2 5	44	22 00
65	2	1	0	6 5	83 5	16 70
70	2	6 5	0	1 5	335	83 75
75	0	0	0	1	37	7 40
80	0	0	0	0	78 5	13 08
85	0	0	0	2	54	10 80
90	0	0	0	3	47	7 83
95	0	0	0	5 5	137 5	27 50
100	0	0	0	2	70	8 24
105	0	0	0	1 5	17 5	5 83
110	0	0	0	1 5	50 5	11 22
115	2	0	0	10	46 5	9 30
120	0	0	0	12	110	15 71
125	0	0	0	1	28	7 00
130	0	0	0	1	63 5	15 88
135	0	0	1 5	11	85 5	14 25
140	0	0	0	4 5	25 5	3 64
145	0	0	0	7	64 5	10 75
150	0	0	0	1	127	21 17
155	0	0	0	3 5	43 5	14 50
160	0	0	0	2 5	32	12 80
165	0 5	0	0	2 5	31 5	6 30
170	0	0	0 5	0 5	19	3 17
175	2	1	1	4	86 5	14 42
180	0	0	0	1	8 5	1 42
188	1	0	3	4 5	50	25 00
193	0	0	0	6 5	80	14 55
198	0	0	2	13	152 5	25 42
203	0	0	0	3	84 5	12 07
208	0	0	0	11	55	27 50
213	0	0	0	6 5	39 5	19 75
218	0	0	0	0	11 5	2 30
223	0	0	0	0	51 5	8 58

Cal ka BP (2000)	CC	Start depth (cm)	*Chironomus anthracinus-type*	*Sergentia*	*Stictochironomus*	*Corynocera ambigua-type*	*Corynocera oliveri-type*	*Cladotanytarsus mancus-type*	*Micropsectra radialis-type*
4 445	6	228	4	2 5	0	0	0	0	0
4 606	6	233	8	1	0 5	0	0	0	0
4 766	7	238	10 5	12 5	0 5	0	1	0	0
4 929	7	243	1	0	1	0	0	0	0
5 099	5	248	1	0	0	0	0	0	0
5 304	6	254	7	2	1	0	0	0	0
5 440	6	258	5	0 5	0	0	0	0	0
5 611	7	263	3	0	1	0	0	0	0
5 781	5	268	2	4	0	0	0	0	0
5 952	4	273	3	1	0	0	0	0	0
6 122	4	278	1	0	0	0	0	0	0
6 395	4	286	2	0	1	0	0	0	0
6 565	1	291	5 5	1	0	0	0	0	0
6 684	2	296	6	3 5	1	0	0	0	0
6 789	2	301	5 5	19 5	0	0	0	0	0
6 894	1	306	5	8	0	0	9	0	0
7 000	2	311	10 5	18	5 5	0	0	0	0
7 117	6	316	31 5	19 5	0	0	0	0	0
7 337	2	321	10	15	0 5	0	0	0	1
7 381	2	322	1 5	1	0	0	0	0	0
7 425	4	323	24	4 5	0	0	3	0	1
7 469	2	324	8 5	0 5	1 5	0	6	0	0
7 513	4	325	12	6	3	0	3	0	0
7 557	4	326	14	8	2	0	3	0	0
7 601	3	327	8 5	9	4	0	10 5	0	0
7 645	2	328	5	1	2	0	4	0	0
7 68	5	329	10	5 5	1 5	0	6	0	0
7 733	3 1	330	7	16 5	2	0	8	0	1
7 777	3 75	331	5	6 5	0	0	1	0	0
7 821	2	332	0	1	0	0	0	0	0
7 865	2	333	7	16 5	4	0	19	0	0
7 910	2	334	4 5	6 5	4	0	27	0	0
8 015	2	335	5 5	9	1	0	14	0	0
8 120	2	336	0	0	2	0	0	0	0
8 225	2	337	2	3	0	0	0	0	0
8 33	3 25	338	1	4 5	0	0	8	0	0
8 436	2	339	0	0 5	0	0	0	0	0
8 541	3	340	0	1	0	0	1	0	0
8 647	6	341	0	2	0	0	1	0	0
8 752	4	342	0	1	1	0	0	0	0
8 857	6	343	0	0	2	0	0	0	0
8 963	3 35	344	0	3 5	0	0	2	0	0
9 068	2	345	0	0	1	0	4	0	0
9 173	2	346	0	0	0	0	0	0	0
9 279	2	347	0	0	0	0	0	0	0
9 384	2	348	0	0	0	0	0	0	0
9 489	4	349	0	3	1	0	1	0	0
9 595	3 5	350	0	0	1	0	1	0	0
9 609	6	351	0	3	0	0	0	0	0
9 682	5	356	0	0	1 5	0	2	0	0
9 755	5	361	0	1	1	0	0	0	0
9 828	4	366	0	1	0	0	1	0	0
9 901	2	371	4 5	7	2	0	5	0	0
9 989	4	377	1	5 5	3	0	3	0	0
10 062	4	382	3 5	0	3	0	4	0	0
10 135	2	387	0	1	1	0	0	0	0
10 208	2	392	0	1	0	0	0	0	0

Start depth (cm)	*Micropsectra insignilobus-type*	*Paratanytarsus austriacus-type w mandibles*	*Paratanytarsus austiacus/penicillatus-type*	*Paratanytarsus penicillatus-type w mandibles*	*Tanytarsus lugens-type w mandibles*	*Tanytarsus lugens/mendax-type*	*Tanytarsus mendax-type w mandibles*	*Tanytarsina-other*
228	1	0	1	0	0	0	0	0
233	0	0	1	0	0	0	0	0
238	0	0	4 5	0	0	0	0	7
243	0	0	0 5	0	0	0	0	0
248	0	0	2	0	0	0	0	3
254	0	0	6	0	1	0	0	0 5
258	0	0	0	0	1	0	0	0
263	0	0	0	0	0	0	0	0
268	0	0	4	0	0	0	0	1
273	0	0	2	0	0	0	0	0
278	0	0	2	0	0	0	0	0
286	0	0	0	0	0	0	0	0
291	1	0	0 5	0	0	1	0	0 5
296	0	0	1	0	0	0	0	0 5
301	0	0	1	0	0	0	0	4 5
306	3 5	0	2	0	0	1	0	5
311	2	0	4	1	0	0	0	0 5
316	3	0	6 5	0	0	0	0	4 5
321	2 5	3	10 5	0	0	0	0	5
322	1	0	0	0	0	0	0	2
323	22 5	0	19 5	0	0	0	0	22
324	8	2	1	0	0	0	0	6 5
325	11	0	3	0	0	0	0	16 5
326	6 5	0	1	0	0	0	0	31
327	30	0	9	0	0	0	0	37
328	16	0	5	0	0	0	0	8 5
329	44 5	0	1	0	0	5	0	28
330	45 5	0	8	0	0	0	0	25 5
331	15	0	0	0	0	0	0	7 5
332	9 5	0	0	0	0	0	0	3 5
333	75 5	0	19 5	0	0	0	0	26
334	38 5	1	17	0	0	0	0	21
335	51	1	11 5	0	0	0	0	15
336	17 5	2	11	0	0	0	0	9
337	25 5	0	1	0	0	0	0	8
338	39 5	1	4	0	0	0	0	13
339	15	0	7	0	0	2	0	11 5
340	15	1	3	0	0	0	0	4
341	36	0	5	0	0	0	0	19 5
342	12 5	0	1	0	0	0	0	8 5
343	14	0	0	0	0	0	0	4 5
344	27 5	0	3	0	0	0	0	13 5
345	18 5	0	10 5	0	0	1	0	2
346	5	0	0	0	0	0	0	0
347	9	0	2	0	0	0	0	0
348	9	0	0	0	0	0	0	1
349	29	0	1	0	0	1	0	10
350	24	0	0	0	0	1	0	20 5
351	43	0	1	0	0	0	0	6 5
356	43 5	1	2	0	0	1 5	0	10 5
361	21	0	0	0	0	0	0	3 5
366	36 5	0	0	0	5	1	0	3 5
371	0 5	0	8	0	0	0	0	1
377	55 5	2	8	0	0	1	0	21 5
382	22	0	2	0	0	0	0	5 5
387	26	0	0	0	0	0	0	8
392	0	0	0	0	0	0	0	0

Start depth (cm)	*Tanyarsina pallidicornis-type*	*Protanypus*	*Pseudodiamesa*	*Monodia mesa*	*Abiskomyia*	*Brillia/Eur yhapsis spp*	*Corynone ura/Thien emanniell a spp*	*Corynoneura Arctica*
228	1	0	0	0	9	0	0	0
233	0	0	1	0	24	0	0	0
238	0	0 5	1	0	9	0	2	12
243	0	0	0	0	2	0	0	0
248	0	0	0	0	0	0	0	0
254	0	0	0	0	3	0	0	0
258	0	0	0 5	0	5	0	0	0
263	0	0	0	0	1 5	0	0	0
268	0	0	0	0	7 5	0	0	0
273	0	0	1	0	0	0	0	0
278	0	0	0 5	0	0	0	0	0
286	0	0	0	0	0 5	0	0	0
291	0	0	0	0	0	0	0	0
296	0	0	0	0	0	0	0	0
301	0	0	1 5	0	0	0	0	0
306	0	0 5	2	0	0	0	0	0
311	0	0	6	0	0	0	0	0
316	0	0	3 5	0	0	0	0	0
321	0	0	0	0	0	0	0	0
322	0	0	1	0	0	0	0	0
323	0	0	2 5	0	0	0	1	0
324	0	0	0	0	0	0	0	0
325	0	1	0	0	0	0	0	0
326	0	1	0	0	0	0	2	0
327	0	1	0	0	0	0	2	0
328	0	0	1	0	0	0	0	0
329	0	4	0	0	0	0	0	0
330	0	2	0	0	0	0	4	0
331	0	0	0	0	0	0	0	0
332	0	0	0	0	0	0	0	1
333	0	2	0	0	0	0	0	0
334	0	0	0	0	0	0	0	1 5
335	0	0	0	0	0	0	0	0
336	0	1	0	0	0	0	0	0
337	0	0	0	0	0	0	0	0
338	0	0	0	0	0	0	0	1
339	0	0	0	0	0	0	0	0
340	0	0	0	0	0	0	0	0
341	0	1	0	0	0	0	2	0
342	0	0	0	0	0	0	0	0
343	0	1	0	0	0	0	0	0
344	0	1	0	0	0	0	0	0
345	0	0	0	0	0	0	0	0 5
346	0	0	0	0	0	0	0	0
347	2	0	0	0	0	0	0	0
348	2 5	0 5	0	0	0	1	0	0
349	0	1 5	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0
351	0	0	0	0	0	0	0	0
356	0	3 5	0	0	0	0	0	0
361	0	0	0	0	0	0	0	0
366	0	1	0	0	0	0	0	0
371	0	0	0	0	0	0	0	0
377	0	0	0	0	0	0	2	0
382	0	0	0	0	0	0	0	0
387	0	0	0	0	0	0	0	0
392	0	0	0	0	0	0	0	0

Start depth (cm)	*Cricotopus/Orthocladius spp*	*Orthocladius type S*	*Ortho 1*	*Ortho T1*	*Cricotopus MC*	*Cricotopus 1*	*Cricotopus 2*	Cricotopus cylindraceus-type
228	2	0	0	0	0	8	4	0
233	0	0	0	0	0	2	1	0
238	11	0	0	0	0	0	0	0
243	1	0	0	0	0	0	0	0
248	0	0	0	0	0	6	2	0
254	5	0	0	0	0	1 5	3	0
258	0	0	0	0	0	1	1	0
263	0	0	0	0	0	2 5	0	0
268	18	0	0	0	0	0	0	0
273	0	0	0	0	0	0	0	0 5
278	0	0	0	0	0	1	0	0
286	0	0	0	0	0	1	1	0
291	2 5	0	0	0	0	0	0	0
296	0	0	0	0	0	1	0	0
301	0	0	0	0	0	0	0	0
306	1 5	0	0	0	0	0	0	0
311	2	0	0	0	0	0	0	0
316	0	0	0	0	0	0	0	0 5
321	5 5	0	0	0	0	0	0	0
322	1 5	0	0	0	0	0	0	0
323	6	0	0	0	0	0 5	2	0
324	0	0	0	0	0	0	0	0 5
325	1 5	0	0	0	0	0	0	0
326	2	0	0	0	0	0	0	0
327	11 5	0	0	0	0	0	0	1
328	0	0	0	0	0	0	0	0
329	4 5	0	0	0	0	0	0	0
330	3	0	0	0	0	0	0	0
331	0	0	0	0	0	0	0	0
332	0	0	0	0	0	0	0	1 5
333	0 5	0	0	1	0	0	0	1
334	0	0	0	1 5	0	0	0	1
335	0	0	0	2 5	0	0	0	0 5
336	0 5	0	0	0	0	1	0	1
337	0	0	0	0	0	0	0	0
338	0	0	1	0	0	0	0	0
339	0 5	0	0	0	0	0 5	1	1
340	0	0	0	0	0	0	0	0
341	2 5	0	0	0	0	0	0	0
342	0 5	0	0	0	0	0	0	0
343	1	0	0	0	0	0	0	0 5
344	7	0	0	0	0	0	0	0
345	0	0	0	0	0	0	0	0
346	0	0	0	0	0	0	0	0
347	2 5	0	0	0	0	0	0	0
348	0	0	0	0	0	0	0	0
349	1	0	0	0	0	0	0	0
350	1 5	0	0	0	0	0	0	0
351	7	0	0	0	0	0	0	0
356	0	0	0	0	0	0	0	1
361	0	0	0	0	0	0	1	0
366	2	0	0	0	0	0	0	1
371	0 5	1	0	0	0 5	0	0	0
377	4 5	0	0	0	0	2	1	1
382	0 5	0	0	0	0	0	0	0
387	0	0	0	0	0	0	0	0
392	0	0	0	0	0	0	0	0

Start depth (cm)	Cricotopus intersectus	Cricotopus laricomalis-type	Cricotopus sylvestris-type	*Eukiefferiella /Tvetenia spp*	*Heterotrissocladius maeari Type1 dark*	*Heterotrissocladius maeari Type1 pale*	*Heterotrissocladius maeari Type2 dark*	*Heterotrissocladius maeari Type2 pale*
228	0	0	0	0	0 5	0	0 5	0
233	0	0	0	0	0	1	0	0
238	0	0	0	0	6 5	0	0 5	0
243	0	0	0	0	0	0	0	1
248	0	0	0	0	0	2 5	0	0
254	0	0	0	0	0	0	0	0
258	0	0	0	0	0	0	0	0
263	0	0	0	0	0	0	0	0
268	0	0	0	0	0	0	0	0
273	0	0 5	0	0	1	2	0	0
278	0	0 5	0	0	0	0	0	0
286	0	0	0	0	0	0	0	0
291	0	0	0	0	0	1 5	0 5	0
296	0	0	0	0	0	0 5	0	0
301	0	0	0	0	0	5	0	0
306	0	0	0	0	1 5	0	0	0
311	0	0	0	0	0 5	3	0	0
316	0	0	0	0	3 5	0	1	0
321	0	0	0	0	2	0	0	0
322	0	0	0	0	0	0	0	0
323	0	0	0	0	4 5	2 5	0 5	0
324	0	0	0	0	4	0	0 5	0
325	0	0	0	0	5 5	0	1	0
326	0	0	0	0	1	0	1	0
327	0	0	1	0	4	3	4 5	0
328	0	0	0	0	0	1 5	0	0 5
329	0	0	0	0	1 5	1 5	0	0
330	0	0	0	0	8	3 5	6	1 5
331	0	0	0	0	2	0	6	0
332	0	0	0	0	4 5	0	0	0
333	0	0	0	0	33 5	0	9 5	0
334	0	1 5	0	0	25	0	9	0
335	0	0	0	0	29 5	0	8 5	0
336	0	1 5	0	0	9 5	0 5	4 5	0 5
337	0	0	0	0	0 5	0	1	0
338	0	0	0	0	10 5	0	2	0
339	0	1	0	0	8 5	2	0	0 5
340	0	0	0	0	9	0	1 5	0
341	0	0	0	0	7 5	2	7 5	2 5
342	0	0	0	0	2 5	0 5	6 5	0
343	0	0	0	0	6 5	1 5	3	0
344	0	0	0	0	19 5	0	15 5	0
345	0	0	0	0	8	0	0	0
346	0	0 5	0	0	0	0 5	0	0
347	0	0	0	0	0	1	0	0
348	0	0	0	0	1 5	1 5	1	0
349	0	0	0	0	7	6	2 5	0
350	0	0	0	0	3 5	1 5	4 5	0
351	0	0	0	0	9	1	5 5	0
356	0	3 5	0 5	0	9 5	0	6 5	0
361	0	0	0	0	15 5	0	0	0
366	1	0	0	0	23 5	0	7	0
371	0	0	0	0	0	10 5	1 5	0
377	0	0	0	0	1	0	0 5	0
382	0	0	0	0	0 5	0	3	0
387	0	0	0	0	1	2 5	0	0
392	0	0	0	0	0	0	0	0

Start depth (cm)	*Heterotris socladius marcidus*	*Heterotris socladius subpilosis*	*Heterotris socladius grimshawi*	*Hydrobaenus /Oliveridia spp*	*Limnophyes*	*Mesocrico topus*	*Metriocnemus terrester*	*Metriocnemus eurynotus*
228	0	0	0	0	0	0	0	0
233	0	0	0	0	0	0	0	0
238	0	0	0	0	0	0	0	0
243	0 5	0	0	0	0	0	0	0
248	0	0	1	0	0	0	0	0
254	0	0	0	0	0	0	0	0
258	0	0	0	0	0	0	0	0
263	0	0	0	0	0	0	0	0
268	0	0 5	0	0	0	1	0	0
273	0	0	0	0	0	0	0	0
278	0	0	0	0	0	0	0	0
286	0	0	0	0	0	0	0	0
291	0	0	0	0	0	0	0	0
296	0	0	0	0	0	0	0	0
301	0	0	0	0	0	0	0	0
306	0	0	0	0	0	0	0	0
311	0	0	0	0	0	0	0 5	0
316	0	0	0	0	0	0	0	0
321	0	0	0	0	0	0	0	0
322	0	0	0	0	0	0	0	0
323	0	0	0	0	0	0	3	0
324	0	0	0	0	0	0	0	0
325	0	0	0	0	0	0	0	0
326	0	0	0	0	0	0	1	0
327	0	0	0	0	0 5	0	0	0
328	0	0	0	0	0	0	0	0
329	0	0	0	0	0	0	0	0
330	0	0	0	0	0	0	0	1
331	0	0	0	0	0	0	0	0
332	0	0	0	0	0	0	0	0
333	0	0	0	0	0	0	0	0
334	0	0	0	0	0	0	0	0
335	0	0	0	0	0	0	0	0
336	0	1	0	0	0	0	0	0
337	0	0	0	0	0	0	0	0
338	0	0	0	0	1	0	0	0
339	0	0	0	0	0	0	0	0
340	0	1	0	0	0	0	0	0
341	0	0	0	0	0	0	0	0
342	0	1	0	0	0	0	0	0
343	0	0	0	0	0	0	0	0
344	0	0	0	0	0 5	0	0	0
345	0	0	11 5	0	0	0	0	0
346	0	0	0	0	0	0	0	0
347	0	0	0	0	0	0	0	1
348	0	0	0	0	0	2	0	0
349	0	0 5	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0
351	0	1	0	0	0	0	0	0
356	0	2	0	0	0	1	0	0
361	0	0	4 5	0	0	0	0	0
366	0	0	0	0	0	0	0	0
371	0	0	0	0	0	0	0	0
377	0	0	0 5	0	0	0	0	0
382	0	0	0	0	0	0	0	0
387	0	0	0	0	0	0	0	0
392	0	0	0	0	0	0	0	0

Start depth (cm)	Paracladius	Parakief feriella nigra	Parakief feriella bathophila-type	Parakief feriella spB	Parakief feriella triquetra type	Psectrocladius (Psectrocladius)	Pseudosmittia	Smittia	Zalutschia spB
228	4 5	0	0	0	0	0	0	0	1 5
233	6	0	0	0	0	0	0	0	1 5
238	48	10 5	0	0	0	0	0	0	10
243	2	0	0	0	0	0	0	0	0
248	7	1	0	0	0	0	0	0	2 5
254	1	4	0	0	0	0	0	0	5
258	0 5	0	0	0	0	0	0	0	0 5
263	0	0	0	0	0	0	0	0	1
268	5	7 5	0	0	0	0	0	0	12
273	38	1	0	0	0	0	0	0	21 5
278	20 5	0	0	0	0	0	0	0	10
286	0 5	1 5	0	0	0	0	0	0	2
291	0	0	0	0	0	0	0	0	1
296	1 5	0	0	0	0	0	0	0	2 5
301	4	3	0	0	0	0	0	0	9 5
306	30	2 5	0	0	0	0	0	0	22 5
311	2 5	7	0	0	0	0	0	0	15 5
316	2	3	0	0	0	1	0	0	0
321	0 5	1	2	0	0	0	0	0	1
322	0	0	0	0	0	0	0	0	0
323	4	10	0	0	0	0	0	0	3 5
324	3	4 5	0	0	0	0 5	0	0	0
325	3 5	7	0	0	0	0 5	0	0	0
326	6	16 5	0	0	0	0	0	0	1 5
327	33	66 5	0	0	0	0	0	0	0
328	0	19	0	0	0	0	0	0	0
329	7 5	16	0	0	0	0	0	0	0
330	9	21 5	0	0	0	0 5	0	0	4
331	1	0 5	0	0	0	0	0	0	0
332	0	4	0	0	0	0 5	0	0	0
333	8 5	3	0	0	0	2	0	0	2
334	11 5	14	0	0	0	0 5	0	0	1
335	2 5	9	0	0	0	0	0	0	0
336	0	8 5	0	0	0	0	0	0	0 5
337	0	0	0	0	0	0	0	0	0
338	2 5	8	0	0	0	1	0	0	0
339	1 5	5	0	0	0	0 5	0	0	0
340	0	6 5	0	0	0	0	0	0	0
341	2 5	15	0	0	0	2	0	0	1 5
342	1	3	0	0	0	0	0	0 5	3
343	0	0	0	0 5	0	1	0	0	0
344	0	7 5	0	0	0	1	0	0	0
345	1	1 5	0	0	0	0 5	0	0	0 5
346	0	2 5	0	0	0	0	0	0	0
347	0	2	0	0	0	0	0	0	0
348	0	1 5	0	0	0	0	0	0	0
349	2 5	14 5	0	0	0	1	0	0	0
350	0 5	10 5	0	0	0	1 5	0	0	1
351	3	7	0	0	0	0	0	0	0
356	0	16 5	0	0	0	0	0	0	0
361	0	6 5	0	0	0	0	0	0	0
366	0 5	0	0	0	0	0	1	0	0
371	13	1 5	0	0	0	0	0	0	8 5
377	1	0	0	0	0	0	0	0	0 5
382	7	0 5	0	0	0	0	0	0	0 5
387	0 5	0	0	0	0	0	0	0	0 5
392	0	0	0	0	0	0	0	0	0

Start depth (cm)	Tanypodinae-UK	*Procladius*	Unknown	Unidentifiable	TOTAL HC	Concentration (HC/CC)
228	0	0	0	1	39 5	6 58
233	0	0	0	4 5	47	7 83
238	1	1 5	0	9	149 5	21 36
243	0	0	0	1	9	1 29
248	0	0	0	7	28	5 60
254	0	0	0	1 5	40	6 67
258	0	0	1	4	16	2 67
263	0	0	0	0 5	9	1 29
268	0	0	0	2	62 5	12 50
273	0	0	0	6	71 5	17 88
278	0	0	0	1	35 5	8 88
286	0	0	0	0	9 5	2 38
291	0	0	0	0	15	15 00
296	0	0	0	1	17 5	8 75
301	0	0	0	7	53 5	26 75
306	0	0	0	0	94	94 00
311	0	0	0	4 5	78 5	39 25
316	0	1	0	1 5	80 5	13 42
321	0	0	1	4 5	60 5	30 25
322	0	0	0	1	8	4 00
323	0	0	3	13	139 5	34 88
324	0	0	0	2	47	23 50
325	0	3	1	4	78 5	19 63
326	0	1	0	12 5	98 5	24 63
327	2	0	1	3	239	79 67
328	0	0	0	3 5	63 5	31 75
329	0	3	0	1	139 5	27 90
330	3	1	1	5 5	182 5	58 87
331	0	0	0	0	44 5	11 87
332	1	0	0	0	26 5	13 25
333	1	0	0	9	231 5	115 75
334	1	1	0	7 5	188	94 00
335	2	0	0	4	162 5	81 25
336	1	0	0	0 5	72 5	36 25
337	0	0	1	3 5	42	21 00
338	0	0	0	3 5	98	30 15
339	0	2	0 5	5	60 5	30 25
340	0	0	0	3	43	14 33
341	0	2	1	4	112 5	18 75
342	0	0	0	1 5	42 5	10 63
343	0	0	0	1	35 5	5 92
344	0	2	1 5	1	105	31 34
345	0	0	0	1 5	60 5	30 25
346	0	0	0	1	8 5	4 25
347	0	0	0	2	19 5	9 75
348	0	0	0	0	21 5	10 75
349	0	2	0	2	84 5	21 13
350	0	2	0	3	74	21 14
351	0	1	0	3 5	88	14 67
356	0	0	1	3	107	21 40
361	0	1	0	4	55	11 00
366	0	0	2	1 5	87	21 75
371	3	0	0	7	68	34 00
377	1	11	3	1	129 5	32 38
382	0	0	1	0	53	13 25
387	0	0	0	5 5	40 5	20 25
392	0	0	0	0	1	0 50

Appendix 6:

Lake JR01 chironomid head capsule raw counts

Cal years ka	Depth (cm)	CC	*Chironomus anthracinus-type*	*Sergentia*	*Stictochir onomus*	*Corynocera ambigua-type*	*Coryno cera oliveri-type*	*Microps ectra undif*	*Microps ectra radialis-type*	*Microps ectra insignil obus-type*	*Parat anyta rsus undif*
0 047	1 5	0 1	0	0	0	0	0	5 5	2 5	3	0
0 101	3 5	2	0	10	0	0	0	18	13	11	6
0 128	4 5	0 2	0	3	0	0	0	13	2	6	1
0 157	5 5	2	0	10	0	0	0	11 5	7 5	12	3
0 231	7 5	2	0	24 5	0	0	0	20	14	12	4
0 268	8 5	0 1	0	0 5	0	0	1	0 5	1	0	0
0 305	9 5	2	0	14 5	0	0	2	24	17 5	5	2
0 342	10 5	1	0	13	0	0	1	12 5	7	6	4
0 379	11 5	2	0	14 5	0	0	6	24	5	18	0 5
0 416	12 5	0 2	0	1 5	0	0	1	5	0	1	0
0 452	13 5	2	0	4 5	0	0	0	12	8	12	1 5
0 526	15 5	2	0	21 5	0	0	0	18 5	3	13	0
0 599	17 5	2	11	0 5	0	0	1	8	7	13	1
0 671	19 5	2	0	13	0	0	1	12	1	7	0
0 842	24	1 5	0	8	0	0	4	14 5	4	12	0
0 982	28	2	0	15	4	0	0	30 5	2	8	0
1 153	33	2	0	6 5	0	0	0	11 5	1 5	4	0
1 473	43	2	0	6 5	0	0	1	14	6	6	2 5
1 503	44	1 45	0	22	3	0	1	26	8	5	0
1 533	45	3	0	10 5	0 5	0	1	22 5	4	9	0
1 650	49	2 5	13 5	0	0	0	0	8	1	5	1
1 705	51	2 5	0	20 5	1	0	2	15	4	4	1
1 787	54	3 75	0	26 5	2 5	0	1	22	5	7	2 5
1 890	58	2	1	20	2	0	0	47	8 5	10	2
1 916	59	0 5	0	3	0	0	0	2	1	1	0
1 941	60	2	0	13	0	0	2	3	0	5	1
2 034	64	3	0	40 5	0	0	1	30 5	5	13	1
2 144	69	1	0	7 5	0	0	0	3	1	2	2
2 165	70	2	0	12 5	0	0	1	10 5	2	8	2
2 226	73	2	0	17 5	5	0	4	53	8 5	10	5
2 445	85	2 25	0	24	3	0	0	18	1	4	4
2 575	93	2 25	0	19 5	3	0	4	35 5	4 5	20	6 5
2 798	108	2 5	0	18	2	0	0	12	0	3	2
2 869	113	2	0	15 5	5	0	1	15	1 5	1	3
2 940	118	3	0	33	4	0	0	16 5	5 5	4	6
3 010	123	3	0	31	3	0	0	13 5	0	8	4
3 082	128	2	0	24 5	1	0	3	9	0	12	1
3 154	133	3	0	25 5	4	0	0	12	2	0	1
3 229	138	2	1	11 5	0	0	8	14 5	1	7	5 5
3 306	143	3	1	23	1	0	7	23 5	2	11	12
3 386	148	2	14	0	0	0	5	7	1	6	2
3 470	153	3	0	26	0	0	0	6	2	6	0
3 558	158	2 25	1	31 5	1	0	5	19 5	1	10	4
3 649	163	2 75	2	31	1	0	5 5	19 5	6 5	10	6 5
3 744	168	2	3	14	1	0	2	5	0	1	0

Depth (cm)	*Paratanytarsus austriacus-type w mandibles*	*Paratanytarsus austriacus-type no mandibles*	*Paratanytarsus austiacus/penicillatus-type*	*Paratanytarsus penicillatus-type w mandibles*	*Tanytarsus undif*	*Tanytarsus lugens-type w mandibles*	*Tanytarsus lugens-type no mandibles*	*Tanytarsus lugens/mendax-type*
1 5	0	0	0	0	0	0	4	0
3 5	1	0	0	0	5	1	2	0
4 5	0	0	0	0	1	0	1	0
5 5	0	0	0	0	3	0	4	0
7 5	0	0	0	0	2	1	12	0
8 5	0	0	0	0	1	0	0	0
9 5	0	0	0	0	2	0	0	0
10 5	0	0	0	0	1	0	1	0
11 5	0	0	0	0	0	0	2	0
12 5	0	0	0	0	1	0	0	0
13 5	0	0	0	0	4	1	1	0
15 5	0	0	0	0	0	0	2	0
17 5	0	0	0	0	0	1	6	0
19 5	0	0	0	0	1	0	0	0
24	0	0	0	0	0	0	1	0
28	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0
43	0	0	0	0	1	0	1	0
44	0	0	0	0	0	0	0	0
45	0	0	0	0	2	0	2	0
49	0	0	0	0	1	0	1	0
51	0	0	0	0	4	0	0	0
54	0	0	0	3	0	0	1	0
58	0	0	0	0	2	0	0	0
59	0	0	0	0	1	0	0	0
60	1	0	0	0	0	0	0	0
64	0	0	0	0	0	0	1	0
69	0	0	0	0	1	0	3	0
70	0	0	0	0	0	1	0	0
73	0	0	0	0	2	3	0	0
85	0	0	0	0	0	1	0	0
93	3 5	0	0	0	3	5	8	0
108	1	0	0	0	5	2	6	0
113	0	0	0	2	0	3	0	0
118	0	0	0	0	0	1	9	0
123	0	0	0	0	0	2	9	0
128	0	0	0	0	0	1	0	0
133	0	0	0	0	1	0	6	0
138	0	0	0	0	0 5	5	0	0
143	1	0	0	0	2	2	8	0
148	0	0	0	0	9 5	0	0	0
153	0	0	0	0	1	0	4	0
158	0	0	0	0	1 5	2	12	0
163	0	0	0	0	2	0	2	0
168	0	0	0	0	0	1	0	0

Depth (cm)	*Tanytarsus mendax-type w mandibles*	*Tanytarsina -other*	*Diamesa*	*Protanypus*	*Pseudo diamesa*	*Abiskomyia*	*Cory noneura arctica-type*	*Crico topus/ Ortho cladiu s spp*	*Crico topus inters ectus -type*	*Crico topus sp1*
1 5	0	1 5	0	0	1	2	0 5	0	0	0
3 5	0	29 5	0	1	6	18 5	6	0	0	1 5
4 5	0	2	0	0 5	2 5	6	4	0	0	0
5 5	0	12	0	1	9	17	4	1	0 5	0
7 5	0	23 5	0	2	6	22	2	1	1	1
8 5	0	0	0	0	0	1	0	0	0	0
9 5	0	16	0	0 5	6	13	2	0 5	0	2
10 5	0	24	0	2	6 5	16	4	0	0	0
11 5	0	27 5	0	0 5	9 5	27	4	0 5	0	0
12 5	0	3 5	0	0 5	1	7	0	0	0	0
13 5	0	11	0	0	5 5	17 5	1	0	0	0
15 5	0	12 5	0	1 5	6 5	13	1	1	1 5	0
17 5	0	15 5	0	1 5	4	31 5	2	0	3	2 5
19 5	0	8	0	3 5	7 5	28 5	4	1	0	1
24	0	15	0	2 5	2 5	18 5	1	1 5	0	1
28	0	10 5	0	7	2 5	37	4	0 5	0	0
33	0	5	0	4 5	3	17	3	0	0	0
43	0	13	0	3	2 5	21	1	0	0	0
44	0	12 5	0	6 5	4	37 5	2	0	0	0
45	0	11 5	0	3	1 5	20	2	2	0	0
49	0	3	0	0	3	19	1	0	0	0
51	0	6	0	4	6 5	37 5	3	0	2	0
54	0	16	0	5 5	4	40	3 5	2 5	0	4
58	0	13	0	3 5	6 5	29 5	8	0	0	1
59	0	0	0	0 5	0	1 5	0	0 5	0	0
60	0	4	0	1	0 5	10 5	0	0	0 5	0
64	0	14	0	2 5	0	16 5	3	3	0	0
69	0	2	0	1	0	20	1	0 5	0	0
70	0	7	0	1	0	13 5	1	0	0	0
73	0	26	0	4 5	0	22 5	14	1	0	2
85	0	6	0	3	3	28	3	0	0	1
93	0	27	0	1	5 5	32 5	5	3 5	0	0
108	0	14 5	0	2	1	9	2	0	0	0
113	0	8	0	4	0 5	12	3	1	0	0 5
118	0	9	0	0	1	24 5	7	1 5	1 5	0 5
123	0	15 5	0	1	0	19	5	0	0	0
128	0	11 5	0	2 5	0	8	1	0	0 5	0
133	0	9	0	1	0	30	2 5	0 5	0	0 5
138	0	14	0	1 5	0	15 5	1	0	0	0
143	0	20	0	4 5	0	11 5	4	1	1	0
148	0	0	0	1	1	10 5	0	0 5	0 5	0
153	0	15 5	0	0 5	0 5	15	0	0 5	0	1 5
158	0	8	0	6	2	7	2	1 5	1	0
163	0	12 5	0	2 5	0	11	3	0	0	0
168	0	12	0	0	1	14	2	0	2	0

Depth (cm)	*Crico topus sp2*	*Crico topus sp3*	*Crico topus sp4*	*Eukiefferiella/ Tvetenia spp*	*Heterotris socladius pale spp*	*Heterotris socladius maeari Type1 dark*	*Heterotris socladius maeari Type1 pale*	*Heterotris socladius maeari Type2 dark*	*Heterotris socladius maeari Type2 pale*	*Heterotris socladius marcidus-type*
1 5	0	0	0	0	0	0	0	0	0	0
3 5	3	3	0	0	0	1	2 5	1	0 5	0
4 5	0	1	0	0 5	0	0	0	0	0	0
5 5	0	0 5	0	0 5	0	0	1 5	0	0 5	0
7 5	1 5	0	0	0	0	0	0 5	0	0	0
8 5	0	0	0	0	0	0	0	0	0	0
9 5	0	0	0	0	0	0 5	1 5	0	0	0
10 5	0	0	0	0	0	2 5	3	0	0 5	0
11 5	2	0	0	2 5	0	0	1 5	0	0	0
12 5	0	0	0	0	0	0	0	0	0	0
13 5	2	0	0	0	0	0	1 5	0	0 5	0
15 5	0	0	0	0	0	0	1 5	0	0	0
17 5	0	0	0	0 5	0	6 5	4 5	1	1 5	0
19 5	0	0	0	1	0	4 5	0 5	2	0	0
24	0	0	0	0	0	4 5	2	1	0	0
28	2 5	0	0	0 5	0	7	1	2 5	0 5	0
33	0	0	0	0	0	1	0 5	2	0	0
43	1	1	0	0	0	3	1	0 5	0	0
44	1	0	0	2	0	4	3	3	0	0
45	0	0	0	1 5	0	4	1 5	0	0	0
49	0	0	0	0 5	0	4	0 5	0 5	0	0
51	2	0	0	0	0	0 5	0	1	0 5	0
54	3 5	0	0	0	1	8 5	1	0 5	0	0
58	4 5	0	0	1	0	2	4	1	0 5	0
59	0	0	0	0	0	0	0	0	0	0
60	6 5	0	0	0	0	0 5	0 5	0	1	0
64	0	0	0	1	0	5 5	2	1 5	0	0
69	0	0	0	0	0	3	2 5	1 5	1	0
70	0 5	0	0	1	0	3	2	0	0 5	0
73	1	0	0 5	0	0	8	5 5	3 5	0	0
85	2	0	0	0	0	2	3 5	1 5	0	0
93	3	0	0	1	0	5	4	4 5	3	0
108	0	0	0	0	0	2	1 5	0 5	0 5	0
113	1	1	0	3 5	0	8 5	5 5	3	2	0
118	1 5	1	0	0	0	7	5 5	1 5	1	0
123	0	0	0	0	0	5 5	3 5	4	2	0
128	1 5	0	0	0	0	1 5	5	1	2	0
133	0	1	0	0 5	0	0 5	3 5	0 5	1 5	0
138	1	0	0	1 5	0	0 5	5	0	0	0
143	1	0	0	0	0	15	6 5	6 5	4	0
148	0	0	0	0	0	4 5	10	2	2 5	0
153	1	0	0	0	0	1	1 5	0	2 5	0
158	0	0	0	0	0	7 5	9	6 5	4	0
163	2	1	0 5	0	0	9 5	8 5	3	2	0
168	0	0	0	0	0	0	1	2	0	0

Depth (cm)	*Heterotris socladius subpilosis -type*	*Heterotris socladius grimshawi -type*	*Hydrobaenus/ Oliveridia spp*	*Limno phyes*	*Mesocrico topus*	*Metrioc nemus eurynot us-type*	*Metrioc nemus fuscipes -type*	*Paracladius*	*Parakief feriella nigra-type*	*Parakief feriella spB*
1 5	0	0	0	0	0	0	0	7	0	0
3 5	0	0	0	0	0	0	0	19 5	0	0
4 5	0	0	0	0	0	0	0	3 5	0	0
5 5	0	0	0	1	0	0	1	17 5	0	0
7 5	0	0	0 5	2	0 5	0	0	27	0	0
8 5	0	0	0	0	0	0	0	1 5	0	0
9 5	0	0	0	0 5	0	0	0	18 5	0 5	0
10 5	0	0	0	1	0	0	0	15	0	0
11 5	0	0	0	0	0	0	0	24	0	0
12 5	0	0	0	0	0	0	0	7	0	0
13 5	0	0	0 5	0	1	0	0	25	0	0
15 5	0	0	0	0	0	0	0	20	0	0
17 5	0	0	0 5	0	0	0	0	44	0	0
19 5	0	0	0	0 5	1	0	0	37 5	0 5	0
24	0	0	0	0	1	0	0	24	1 5	0
28	0	0	0	0	1	0	0	39	2 5	0
33	0	0	0	0 5	1	0	0	18 5	1 5	0
43	0	0	0	0	0 5	0	0	34 5	5	0
44	0	0	0	0	0 5	0	0	51	2 5	0
45	0	0	0	1	0	0	0	32 5	3	0
49	0	0	1	0	1 5	0	0	24 5	0	0
51	0	0	0	1 5	2	0	0	56 5	7	0
54	0	0	1 5	0 5	3	0	0	85 5	5 5	1
58	0	0	1 5	0	5 5	0	0	130 5	8 5	0
59	0	0	0	0	0	0	0	10 5	0 5	0
60	0	0	0	0	2	0	0	17 5	4	0
64	0	0	1 5	0	2	0	0	59 5	3	0
69	0	0	0 5	0	0	0	0	13	0	0
70	0	0	0	0	0 5	0	0	36	0	0
73	0	0	0	0	2 5	1	0	104	0	0
85	0	0	1	1	1	0	0	46 5	3 5	0
93	0	0	0 5	0	3 5	0	0	96 5	3 5	0
108	0	1	0	0	0	0	0	27	0	0
113	0	3	0	0	1	0	0	49 5	3 5	0
118	0	1	0	0	2	0	0	58	0	0
123	0	0	0 5	0	1 5	1	0	42 5	0	0
128	0	0	0	0	3	0	0	46 5	1	0
133	0	1	0	0	1	0	0	35 5	0 5	0
138	0	0	0	1	0 5	0	0	16	0	0
143	0	0	1	0	3 5	0	0	71	0	0
148	0	0	0	0	1	1	0	20	1	0
153	0	0	1	0	0	0	0	23	0	0
158	0	0	0	1	1 5	0	0	79	0	0
163	0	0	0	0	1	0	0	92 5	0	0
168	1	1	0	0	1 5	0	0	41	0	0

Depth (cm)	*Parakief feriella triquetra type*	*Psectrocl adius (Psectrocl adius)*	*Psectrocl adius (Allo & Meso)*	*Zalut schia spB*	*Zalut schia spA*	Pentan eurini-undif	*Procl adius*	UK	UNID MISSING /WORN	UNID INSTAR	SUM ALL HC	SUM IDed HC	Total CC
1 5	0	0 5	0	0 5	0	0	0	0	1	0	29	28	0 1
3 5	0	0	1 5	1	1 5	0	0	0	7	3 5	174 5	164	2
4 5	0	1	0	0	0	1	0	0	2	0	51	49	0 2
5 5	0	1	0	1	1 5	0	0	0	5 5	1	128	121 5	2
7 5	0	0 5	0	4	1	0	2	0	2 5	6	196	187 5	2
8 5	0	1 5	0	0	0	0 5	0	0	0 5	0	9	8 5	0 1
9 5	0	1 5	0	2	0	1	0	0	4	2	139	133	2
10 5	0	2	0	1 5	2	0	0	0	8	1	134 5	125 5	1
11 5	0	0 5	0	0 5	2 5	0	0	0	3 5	5 5	181 5	172 5	2
12 5	0	0	0	1	0	0	0	0	0 5	0	30	29 5	0 2
13 5	0	2	0	2	2	0	0	0	3	1	119 5	115 5	2
15 5	0	0 5	0	1 5	0	0	1	0	6	0	125 5	119 5	2
17 5	0	1 5	0	1 5	1	0	1 5	0	2 5	6 5	181 5	172 5	2
19 5	0	1	0	5	1	0	0	0	7 5	3 5	154	143	2
24	0	3	0	0	0	1	0 5	0	7 5	0	131 5	124	1 5
28	0	2	0	1	3	1	0	0	0	3 5	188	184 5	2
33	0	0 5	0	2 5	0	0	0	0	4	0	88	84	2
43	0	1 5	0	0 5	2 5	0	0	0	6 5	0	136	129 5	2
44	0	1 5	0	5	2 5	1	1	0	11 5	0	217	205 5	1 45
45	0	3 5	0	4 5	4 5	0	1	0	2	3 5	154	148 5	3
49	0	2	0	3 5	0 5	0	0	2	2 5	1	100 5	95	2 5
51	0	5	0	3	0	0	0	0	5 5	3	198	189 5	2 5
54	2	4 5	0	3	2	1	1	0	16	13 5	301 5	272	3 75
58	0	5 5	0	9 5	1 5	3	4	0	23 5	2	362	336 5	2
59	0	1 5	0	3	0	1 5	0	0	1 5	1	30	27 5	0 5
60	0	1	0	3 5	0	0	0	0	0	1	79	78	2
64	0	6	0	22	1	2	1	0	3	4	246	239	3
69	0	1	0	3	2 5	0	0	0	1 5	0	73 5	72	1
70	0	3 5	0	3 5	1	3 5	4	0	0 5	3 5	122 5	118 5	2
73	3	15	0	20	3 5	9 5	6	0	13	7 5	381 5	361	2
85	0	2	0	7	2 5	0	1	0	11 5	0	185	173 5	2 25
93	0	15 5	0	9 5	0 5	3	0 5	0	5	3	348 5	340 5	2 25
108	0	7	0	5	3	0	0	0	3 5	0 5	131	127	2 5
113	1	5	0	11 5	1 5	0 5	5	0	8 5	8	198 5	182	2
118	0	6 5	0	14	0	5 5	3	0	12 5	5 5	249 5	231 5	3
123	0	4	0	6 5	0	11	6	0	10 5	2	211 5	199	3
128	0	2	0	4 5	0	8 5	2	0	7	3	163 5	153 5	2
133	0	5	0	9 5	0 5	4	5	0	6 5	8 5	179 5	164 5	3
138	0	4 5	0	2 5	1	4 5	6	0	4	1 5	135 5	130	2
143	0	12 5	0	5 5	3	14	7	0	1 5	8 5	296	286	3
148	0	2	0	3	0	4	0	0	7 5	0	116 5	109	2
153	0	6	0	1	2	8	1	0	5	6 5	138	126 5	3
158	0	11	0	6	1 5	3 5	5	0	10	3 5	265	251 5	2 25
163	0	4 5	0	8	0 5	5	3	0	11	7 5	274 5	256	2 75
168	0	6 5	0	15	0	2 5	3 5	0	2 5	6 5	142	133	2

Cal years ka	Depth (cm)	CC	*Chironomus anthracinus-type*	*Sergentia*	*Stictochironomus*	*Corynocera ambigua-type*	*Corynocera oliveri-type*	*Micropsectra undif*	*Micropsectra radialis-type*	*Micropsectra insignilobus-type*	*Paratanytarsus undif*
3 841	173	2 75	2	3 5	4	0	2	16 5	2	12	12
3 939	178	2 25	0	14 5	0	0	1	11	0	5	6
4 140	188	1	10	0	0	0	0	2	0	1	1 5
4 160	189	2	0	31 5	3	0	7	12 5	0	2	5
4 200	191	2 25	1	11 5	0	0	1	1	0	1	3
4 240	193	1 25	0	6 5	0	0	0	6	1	1	1
4 260	194	2	2	23	4	0	4	25 5	1	7	6
4 340	198	1	0	17	0	0	3	11 5	0	5	3 5
4 360	199	2 5	1	15 5	0	0	6	7	0	2	3
4 439	203	1	0	6 5	0	0	3	8	0	4	6
4 458	204	2	0	19 5	2	0	15	14	0	11	5
4 536	208	1	1 5	16	0	0	2	6	0	2	1
4 555	209	4	2	25 5	2	0	20	16 5	0	5	5 5
4 630	213	2	1	5	0	0	0	11	0	3	4
4 648	214	3	2	26 5	5	0	0	10 5	2	7	2
4 970	233	3	1	44	2	3	1	23 5	0	10	30 5
5 044	238	1 25	0	15	2	0	0	9	0	12	10
5 059	239	2	0	32 5	0	0	5	37 5	0	16	20
5 115	243	3	2	46 5	1	0	6	64 5	4	20	38 5
5 182	248	1 5	0	10	0	0	0	6	0	2	4
5 194	249	2	1	25	1	0	0	19	0	9	8
5 244	253	3	0	56 5	3	0	0	68	2	30	13 5
5 302	258	1 25	0	7 5	0	0	0	7	0	8	6
5 313	259	2	0	20 5	0	0	3	14 5	0	14	9 5
5 356	263	2 5	0	19 5	1 5	0	1	11 5	1	5	5
5 406	268	1 5	0	15	0	0	0	6	8	0	1
5 416	269	2	0	26	0	0	0	15 5	0	4	3 5
5 452	273	2 5	0	23	1	1	0	10 5	0	4	7
5 495	278	0 5	0	6	0	0	1	0	0	6	3
5 503	279	2 25	0	40	0	0	1	30	6	27	15 5
5 568	288	2 25	0	39 5	0	0	0	18 5	15	0	6
5 670	308	2 75	2	44 5	2	0	4	65 5	1	10	17 5
5 688	313	2	1	16	0	0	0	22 5	0	20	5
5 704	318	3	3	23	2	0	2	23	0	13	17
5 719	323	2	1	13 5	2	0	0	25	0	2	11 5
5 732	328	2 5	0	9	3	0	0	5	0	0	6
5 745	333	3	5	42	3	1	1	31 5	2	16 5	10
5 758	338	3	2	41 5	0	1	1	17 5	4	13	14
5 771	343	2	0	17	0	8	1	8	0	1	5
5 782	347	3	0	36	2	0	1	16	0	10	9 5
5 785	348	1 5	1	9 5	0	0	0	6 5	0	1	1
5 801	353	2	0	19 5	0	0	0	11	0	14	2
5 819	358	2	0	16 5	1	0	0	17	0	11	0

Depth (cm)	*Paratanytarsus austriacus-type w mandibles*	*Paratanytarsus austriacus-type no mandibles*	*Paratanytarsus austiacus/penicillatus-type*	*Paratanytarsus penicillatus-type w mandibles*	*Tanytarsus undif*	*Tanytarsus lugens-type w mandibles*	*Tanytarsus lugens-type no mandibles*	*Tanytarsus lugens/mendax-type*
173	0	0	0	0	2	0	5	0
178	0	0	0	0	3	1	6	0
188	0	0	0	0	0	0	0	0
189	0	0	0	0	0	3	6	0
191	0	0	0	0	0	0	1	0
193	0	0	0	0	0	1	0	0
194	1	0	0	0	2	1	5	0
198	0	0	0	0	6	1	5	0
199	0	0	0	0	5	1	4	0
203	0	0	0	0	0	1	1	0
204	0	0	0	0	3	0	9	0
208	0	0	0	0	2	4	2	0
209	0	0	0	0	5	5	1	0
213	0	0	0	1	9	6	2	0
214	0	0	0	0	5	3	2	0
233	0	0	0	2	14 5	0	29 5	9
238	0	1	0	0	4	2	5	0
239	1	0	0	0	7	9	3	0
243	1	0	0	1	15	21	6	0
248	0	0	0	0	9	6	0	0
249	0	0	0	1	7	20	5	0
253	0	0	0	0	20	15	0	0
258	1	0	0	1	6 5	8	1	0
259	0	0	0	2	6	4	1	0
263	2	0	0	0	3	0	1	0
268	0	0	0	0	3	2	1	0
269	1	0	0	0	8	4	3	0
273	0	0	0	0	10	2	3	0
278	0	0	0	0	3	1	0	0
279	1	1	0	0	10	4	14	0
288	0	0	0	0	18	7	2	0
308	0	0	0	1	13	15	2	0
313	1	0	0	0	15	11	3	0
318	0	0	0	0	5	3	1	0
323	1	0	0	0	12	11	0	0
328	1	0	0	0	9	3	0	0
333	0	0	0	1	30	14	3	0
338	0	0	0	1	9	16	4	0
343	1	0	0	4	0	7	3	0
347	0	0	0	2	9	19	6	0
348	0	0	0	1	1	3	3	0
353	1	0	0	0	2	1	5	0
358	0	0	0	0	1	8	2	0

Depth (cm)	*Tanytarsus mendax-type w mandibles*	*Tanytarsina -other*	*Diamesa*	*Protanypus*	*Pseudodiamesa*	*Abiskomyia*	*Corynoneura arctica-type*	*Cricotopus/ Orthocladius spp*	*Cricotopus intersectus-type*	*Cricotopus sp1*
173	0	9	0	3	1 5	16 5	3	0	0	0
178	0	10	0	0	1	2 5	2	0	0	1
188	0	11 5	0	0	0	7 5	0	0	0 5	1 5
189	0	13 5	0	0 5	0	12	2	0	1	0
191	0	1 5	0	1	0	8	0	0	0	0
193	0	5	0	1	0	13 5	2	0	0	0
194	0	20 5	0	2	0 5	9	2	0 5	0	0
198	0	5	0	0	0	0	1	0	0	0
199	0	17	0	0	0	2	2	0	0	0
203	0	8	0	1	0	0	1	0	1	0
204	0	14	0	0 5	1	0 5	5	2 5	0	0
208	0	7	0	0	0	0	1	0	0	0
209	0	26 5	0	0 5	0	0	3	0	0	1
213	0	10	0	0	0	0	0	0	0	0
214	0	9 5	0	0	0	0	0	0 5	0	0
233	0	47 5	0	0	1	0	1	0 5	1 5	0
238	0	9	0	0	0	0	1	0	0	1
239	0	57	0	0	0	0	9	1 5	3 5	0 5
243	1	66	0	1	0	0	13	2	4 5	0
248	0	17 5	0	0	0	0	2	0	0	0
249	2	39 5	0	0	0	0	4	0	0	0
253	0	32	0	0	0 5	0	11	1	1 5	0 5
258	0	4	0	0	0	0	0	0	0	0
259	0	25 5	0	0	0	0	0	1	0	2 5
263	0	25	0	0 5	0	0	1	0 5	0 5	0
268	0	6	0	0	0	0	0	0	0	0
269	0	16 5	0	0	0	0	3	0	1	0 5
273	1	11	0	0	0	0	1	0	0	2
278	0	10	0	0	0	0	2	0	0	0
279	0	47	0	1 5	0	0	5	3	0	0
288	0	18 5	0	0	0	0	3	2 5	0 5	0
308	1	39 5	0	0	0	0	4	5	4 5	0 5
313	1	25 5	0	0	0	0	5	0	0	0
318	0	19	0	0	0	0	2	0	0	0
323	0	23	0	0	0	1	3	0	0	0
328	0	8	0	0	0	0	0	0	0	0
333	1	53 5	0	0	0	5	3	2	0	0
338	0	42	0	0	0	1 5	5	0	0	0
343	0	14	0	0	0	0	3	1	0	0
347	0	28	0	0	0	0	4	1	1	0
348	0	18 5	0	0	0	0	0	0	0	0
353	0	12	0	0	0	0	1	0	1	0
358	0	27 5	0	0	0	0	1	1	0	0

Depth (cm)	*Cricoto pus sp2*	*Cricoto pus sp3*	*Cricoto pus sp4*	*Eukieffen ella/Tvet enia spp*	*Heterotrisso cladius pale spp*	*Heterotrisso cladius maeari Type1 dark*	*Heterotrisso cladius maeari Type1 pale*	*Heterotrisso cladius maeari Type2 dark*	*Heterotrisso cladius maeari Type2 pale*	*Heterotrisso cladius marcidus-type*
173	0	0	0	0	0	8 5	12	4	6	0
178	0	0	0 5	0	0	1 5	7 5	1	2	0
188	1	0	0	0	0	0 5	1	0	0	0
189	0	0	0	0	0	1	4	3 5	2	0
191	0 5	0	0	0	0	2	0 5	4	0	0
193	0	0	0	0	0	0 5	1	0	0	0
194	0	0	0	0 5	0	2 5	13	4 5	3 5	0
198	1	0	0	0	0	7	4	1 5	2 5	0
199	1	0	1	0	0	2	6 5	0 5	1 5	0
203	0	0	0	0	0	5	2 5	1 5	0	0
204	1	0	0	0	0	3 5	12	2 5	4	0
208	1	0	0	0	0	1	4 5	0 5	2 5	0
209	1	0	0	0	0	4 5	9 5	6 5	3 5	0
213	0	0	0	0	0	1	5	2	0	0
214	1	0	0	1	0	3	5	3 5	3 5	0
233	2	0	0	0	0	7	12 5	5 5	6	0
238	2	0	0	0	0	0	4	3 5	0	0
239	3 5	0	0	0	0	8 5	21	9 5	4	0
243	3	0	0	0	0	18	18	9	7	0
248	0	0	0	0	0	0	5	0	0 5	0
249	2	0	0	0	0	2	9 5	2	1	0
253	0	0	0	0	0	16	23	2 5	2	0
258	0	0	0	0	0	1	3	2	0	0
259	1 5	0	0	0 5	0	7	6 5	2	2 5	0
263	1	0	0	0	0	9 5	3 5	4	1	0
268	0	0	0	0	0	1 5	5 5	0	0 5	0
269	1	0	0	0	0	2	11 5	4 5	1 5	0
273	1 5	0	0	0	0	6	4 5	2	2	0
278	0	0	0	0	0	0	3	0	0 5	0
279	1	1	0	0	0	16	14	7 5	2	0
288	1	0	0	0	0	7 5	11	3 5	3	0
308	0	0	0	0	0	10 5	21	14 5	8 5	0
313	0	0	0	0	0	2 5	14	0	4	0
318	0	0	0	0	0	9	3	0	5	2 5
323	0	0	0	0	0	2	11	4	2 5	0
328	0	0	0	0	0	3 5	5 5	1	3 5	0
333	0	2	0	0	0	8	26	7	5	0
338	1	0	0 5	0	1	9	4	1 5	0	0
343	0	0	0	0	0	0	2 5	0	2	0
347	0 5	0	0	0	0	5 5	7 5	0 5	7	0
348	0	0	0	0	0	0 5	10	0	1 5	0
353	0	0	0	0	0	1 5	15 5	0	4 5	0
358	0	0	1	0	0	4 5	10	0	1 5	0

Depth (cm)	*Heterotrisso cladius subpilosis-type*	*Heterotrisso cladius grimshawi-type*	*Hydrobaenus/ Oliveridia spp*	*Limnoph yes*	*Mesocric otopus*	*Metriocne mus eurynotus -type*	*Metriocn emus fuscipes-type*	*Paracladius*	*Parakieff eriella nigra-type*	*Parakieff eriella spB*
173	0	0	0 5	0	2 5	0	0	66 5	2	0
178	0	0	0	0	0	0	0	40	0	0
188	0	0	0	0	0	0	0	10 5	0	0
189	1	2 5	0	0	0	1	0	38	0	0
191	0	0	0	0	0 5	0	0	9 5	0	0
193	0	0	0	0	0	0	0	7 5	0	0
194	0	1	0	0	1	0	0	61	0	0
198	0	0	0	0	0	0	0	34	0	0
199	0	0	0	0	0	0	0	27 5	0	0
203	0	0	0	1	0	0	0	27 5	0	0
204	1 5	0	0	0	0	0	0	39	0	0
208	0	0	0	0	0	0	0	16	0	0
209	0	0	0	0 5	0	0	0	49	0	0
213	0	0	0	0	0	0	0	9 5	0	0
214	0	1	0	0	0	0	0	21 5	0	0
233	0	1	1	0	0	0	0	35 5	0	0
238	0	0	1	1	0	0	0	16 5	0	0
239	0	0	1	2	0	0	0	68	0	0
243	0	0	2 5	1	0	0	0	133 5	0	0
248	0	0	0	0	0	0	0	9 5	0	0
249	0	0	0	1	0	0	0	45	0	0
253	0	0	1	0	0	0	0	71 5	0	0
258	0	0	1	0	0	0	0	6 5	0	0
259	0	0	0	0	0	0	0	36 5	0	0
263	0	0	0	0	0	0	0	21 5	0	0
268	0	0	0	0	0	0	0	2 5	0	0
269	0	1	0	0	0	0	0	22 5	0	0
273	0	1	0	0	0	0	0	16 5	0	0
278	0	0	0	0	0	1	0	6	0	0
279	0	1	1	0	0	0	0	42 5	0	0
288	0	0	0	0	0	0	0	20	0	0
308	0	0	1 5	0	0	0	0	42	0	0
313	0	0	0 5	0	0	0	0	21	0	0
318	0	0	0	0	0	0	0	33 5	0	0
323	0	0	0 5	1	0	0	0	24	0	0
328	0	0	0	0	0	0	0	8 5	0	0
333	0	1	0	0	0	0	0	45	0	0
338	1	1	1	0	0	0	0	24 5	0	0
343	1	0	0	1	0	0	0	4	0	0
347	4	0	0	1	0	0	0	23	0	0
348	0	0	0	0	0	0	0	9 5	0	0
353	0	0	0	0	0	0	0	9 5	0	0
358	0	0	0	0	0	0	0	17	0	0

Depth (cm)	*Parakieff eriella triquetra type*	*Psectro cladius (Psectroc ladius)*	*Psectro cladius (Allo & Meso)*	*Zalutschia spB*	*Zalutschia spA*	Pentane urini-undif	*Procladius*	UK	UNID MISSING/ WORN	UNID INSTAR	SUM ALL HC	SUM IDed HC	Total CC
173	0	7	0	3 5	3	0	0	0	7 5	2	219	209 5	2 75
178	0	6 5	0	6	0	5	5	0	14 5	6	159 5	139	2 25
188	0	0	0	0	0	0	1	0	0 5	0 5	50 5	49 5	1
189	0	0	0	5 5	1 5	9 5	4	0	4	7	183 5	172 5	2
191	0	0	0	2 5	1	1	0	0	2 5	0 5	54 5	51 5	2 25
193	0	0	0	1 5	0	0	0	0	4	1 5	54	48 5	1 25
194	0	7 5	0	5 5	2 5	14 5	10	0	6 5	4 5	254	243	2
198	0	4 5	0	0 5	1 5	1 5	4	0	8	2	130	120	1
199	0	5 5	0	1	2	2	9 5	0	9	0	134 5	125 5	2 5
203	0	2 5	0	1 5	0 5	6	7	0	4 5	1	101	95 5	1
204	0	7 5	0	1	4	9	20	0	4	13	224	207	2
208	0	2 5	0	0 5	0	4	0	0	0	3	80	77	1
209	0	14	0	0	5	2	15	0	9 5	5 5	244	229	4
213	0	11 5	0	0	0	0	1	0	0	1	83	82	2
214	0	8	0	1	1	0	6	0	1	0 5	132	130 5	3
233	0	22	0	2	0 5	9 5	23	0	4	3	356	349	3
238	0	3 5	0	0	2	6	7	0	12	2	131 5	117 5	1 25
239	0	14	0	0	5 5	13 5	34	0	14 5	5	406 5	387	2
243	0	64	0	1	11	43	57 5	0	15	8 5	706	682 5	3
248	0	3 5	0	0	2	5	6	0	3	5	96	88	1 5
249	0	16 5	0	0	2	17	15 5	0	11	2	268	255	2
253	0	14	0	1 5	2	38	39 5	0	17 5	5	488	465 5	3
258	0	3	0	0	0	0	0	0	4	3 5	78	70 5	1 25
259	0	8 5	0	1	0	1	9	0	11 5	0	191	179 5	2
263	0	3	0	1	0	5	6	0	5	1	139 5	133 5	2 5
268	0	6	0	0	0	1	2	0	0 5	5	66 5	61	1 5
269	0	7	0	2 5	0	4 5	12	0	0 5	4 5	161	156	2
273	0	13	0	1	4	2	6	0	3	1	140	136	2 5
278	0	6 5	0	1	0	5	3	0	2	1	61	58	0 5
279	0	11 5	0	2 5	3 5	34	19	0	16 5	7	386	362 5	2 25
288	0	6 5	0	2 5	2 5	2	3	0	8	3	204	193	2 25
308	0	12	0	0	3 5	30 5	32	0	10 5	6 5	425	408	2 75
313	0	9 5	0	1	0	35 5	27	0	0	1 5	242 5	241	2
318	0	7 5	0	0	0	31 5	25	0	14	0	244	230	3
323	0	5	0	0	0	6	3 5	0	5	0	170 5	165 5	2
328	0	3 5	0	0	0	0	3	0	0	1	73 5	72 5	2 5
333	0	22 5	0	4	1	3 5	6 5	0	4	2 5	363 5	357	3
338	0	10 5	0	0	0	14 5	19 5	0	7 5	16	285	261 5	3
343	0	4 5	0	0	0	1	10	0	0	2	101	99	2
347	0	7 5	0	0	1	20 5	25	0	5 5	6 5	259 5	247 5	3
348	0	4	0	0	0	3 5	2	0	0	5	81 5	76 5	1 5
353	0	2 5	0	1	0	7	7	0	2 5	3	124 5	119	2
358	0	4 5	0	0	0 5	5 5	14	0	1	4 5	150	144 5	2

Cal years ka	Depth (cm)	CC	*Chirono mus anthracin us-type*	*Sergentia*	*Stictochi ronomus*	*Corynocera ambigua-type*	*Corynocera oliveri-type*	*Microp sectra undif*	*Microp sectra radialis-type*	*Microps ectra insignilob us-type*	*Paratany tarsus undif*
6 002	388	2	2	41	0	3	0	25	1	22	7 5
6 011	389	2	1	15 5	1	0	3	22	1	11	5
6 050	393	2	1	27 5	0	5	0	19	0	10	2
6 105	398	2 5	0	22 5	7	0	3	26 5	0	13	14
6 165	403	2	0	17	2 5	1	0	15	0	8	3 5
6 231	408	1	0	12	0	1	0	7	0	8	1
6 245	409	2 5	1	15 5	2	1	0	8	0	1	0
6 301	413	2 5	0	34 5	3	4	1	39 5	1	4	10
6 448	423	1	1	11	0	9	0	6 5	0	5	5 5
6 463	424	2	0	32	0	5	1	22 5	0	6	10 5
6 524	428	0 6	1	9	0	1	0	11	0	8	3
6 539	429	2	0	27 5	1	5	6	26	0	21	23
6 599	433	2	0	14 5	0	2	2	14 5	0	22	13
6 673	438	0 7	1	6 5	0	2	0	7	0	3	2
6 688	439	2	0	18 5	1	3	2	15	0	8	10
6 745	443	3	2	26	5	5	7	25	0	10	9 5
6 814	448	1 5	2	8 5	0	0	2	8	0	4	1
6 827	449	2	1 5	45	0	0	8	26 5	0	17	17
6 878	453	2	0	17	4	3	0	17	0	14	8
6 937	458	1	0	9 5	2	2	0	2	0	2	1
6 991	463	3	0	34	2 5	5	3 5	23	0	17	7
7 040	468	0 5	0	8	1	0	0	1	0	2	2
7 049	469	2	1	23	1 5	0	1	19	2	9	18
7 138	480	3	1	44	1	0	14 5	16	0	9	10 5

Depth (cm)	*Paratanytarsus austriacus-type w mandibles*	*Paratanytarsus austriacus-type no mandibles*	*Paratanytarsus austiacus/penicillatus-type*	*Paratanytarsus penicillatus-type w mandibles*	*Tanytarsus undif*	*Tanytarsus lugens-type w mandibles*	*Tanytarsus lugens-type no mandible*	*Tanytarsus lugens/mendax-type*
388	0	0	0	1	9	7	14	0
389	0	0	0	0	6	9	0	0
393	0	0	0	0	1	6	2	0
398	0	0	0	3	16	4	0	0
403	0	0	0	0	3	0	0	0
408	0	0	0	1	0	0	0	0
409	1	0	0	0	6	1	0	0
413	0	0	0	1	6	7	3	0
423	0	0	0	0	4	2	7	0
424	0	0	0	1	4	12	13	0
428	0	0	0	0	3	2	2	0
429	0	0	0	0	7	3	10	0
433	1	0	0	0	4	4	14	0
438	0	0	0	0	5	0	3	0
439	0	0	0	2	11	7	3	0
443	0	0	0	0	21	6	3	0
448	0	0	0	0	6	0	3	0
449	0	0	0	0	15	4	2	0
453	0	0	0	1	3	6	11	0
458	0	0	0	0	3	2	0	0
463	0	0	0	0	16	3	6	0
468	0	0	0	0	2	0	1	0
469	1	0	0	0	3 5	1	6	0
480	0	0	0	0	7	1	13	0

Depth (cm)	*Tanytarsus mendax-type w mandibles*	*Tanytarsina-other*	*Diamesa*	*Protanypus*	*Pseudodiamesa*	*Abiskomyia*	*Corynoneura arctica-type*	*Cricotopus/Orthocladius spp*	*Cricotopus intersectus-type*	*Cricotopus sp1*
388	1	29	0	0	0	1	5	1 5	1	0
389	2	15	0	0	0	0	1	2	0	0
393	0	21	0	0	0	2 5	0	0	0	0
398	0	25 5	0	0	0	0	14	0 5	0	1 5
403	2	9	0	0	0	0	0	0	0	0
408	2	10	0	0	0	0	1	0	0	0
409	1	11	0	0	0	0	0	0	0	0
413	1	30	0	0	0	0	7	0	0	0
423	0	13	0	0	0	0	0	0 5	1 5	0
424	0	29	0	0	0	0	2	2 5	2 5	0
428	0	9	0	0	0	0	0	0	0	0
429	0	32	0	0	0	1	11	0	0	1
433	1	14 5	0	0	0	0	1	0 5	0	0
438	0	12	0	0	0	0	0	0	0	1
439	1	16	0	0	0	0	0	1	0 5	1
443	0	19	0	0	0	0 5	0	0	0	0
448	0	3	0	0	0	0	0	0 5	0	0 5
449	0	28	0	1	0	1	9	0	0	0
453	1	15	0	0	1	0	1	0	1	0
458	0	7	0	0	0	0	3	0	0	0
463	0	31	0	0	0	0	0	0	0	0
468	0	5	0	0	0	0	1	0	0	0
469	0	29 5	0	0	0	0	3	0 5	0 5	0
480	1	27 5	0	0	0	1	0	3	1	0

Depth (cm)	Crico topus sp2	Crico topus sp3	Crico topus sp4	Eukiefferiella/ Tvetenia spp	Heterotris socladius pale spp	Heterotris socladius maeari Type1 dark	Heterotris socladius maeari Type1 pale	Heterotris socladius maeari Type2 dark	Heterotris socladius maeari Type2 pale	Heterotris socladius marcidus-type
388	0	0	0	0	0	4 5	28	4	2	0
389	0	0	0	0	0	8	12 5	3 5	1 5	0
393	0	0	0	0	0	8	14 5	4 5	2	0
398	1	0	0	0	0	21 5	27 5	12	4 5	2
403	1	0	0	0	0	2 5	9	6	1	0
408	0	0	0	0	0 5	0	1	1 5	2 5	0
409	0	0	0	0	0	1 5	3 5	5	1	0
413	0	0	0	0 5	0	16	20 5	9 5	3	0
423	0	0	0	0	0	4	5	3 5	1 5	0
424	1	0	0 5	0	0	14	22	3	6	0
428	0	0	0	0	0	1	7	3	1	0
429	0	0	0 5	0	0	27	13 5	12 5	2	0
433	2	0	1 5	0	0	7	6 5	3	0 5	0
438	0	0	0	0	0	3 5	6 5	2	1	0
439	2	0	0	0 5	0	12	15 5	3 5	4	0
443	3	0	0	0	0	29 5	8 5	12 5	2 5	0
448	0	0	0 5	0	0	4	3	4 5	2	0
449	2	0	1	0	0	13	27 5	6 5	8	0
453	2	0	0	0	0	20 5	18	9	1 5	0
458	1	0	0	0	0	0	7 5	4 5	1	0
463	1	0	0	0	0	47 5	13 5	14 5	3	0
468	0	0	0	0	0	6 5	9 5	1	0	0
469	0	0	0 5	0	0	27 5	31	9	17	0
480	1	0	3	0	0	27	42 5	21	8 5	0

Depth (cm)	Heterotrıs socladıus subpılosıs -type	Heterotrıs socladıus grımshawı -type	Hydrobaenus/ Olıverıdıa spp	Lımnophyes	Mesocrıco topus	Metrıoc nemus eurynot us-type	Metrıoc nemus fuscıpe s-type	Para cladı us	Parakıef ferıella nıgra-type	Parakıef ferıella spB
388	0	0	0	0	0	0	0	28	0	0
389	0	0	0	0	0	1	0	14 5	0	0
393	0	0	0	0 5	0	1	0	21 5	0	0
398	0	1	0	0	0	0	0	44	0	0
403	0	0	0	0	0	0	0	14	0	0
408	1	2 5	0	0	0	0	0	10	0	0
409	0	3	0	0	0	0	0	13	0	0
413	1	1	0	1	0	0	0	59	0	0
423	0	0	0	0	0	0	0	7 5	0	0
424	1	0	0	0	0	0	0	14	0	0
428	0	0 5	0	0	0	0	0	10 5	0	0
429	1	0	0	0	0	0	0	46 5	0	0
433	1	1 5	0	0	0	0	0	24 5	0	1
438	0	0	0	0	0	0	0	4	0	0
439	0	0	0	0	0	0	0	17 5	0	0
443	0	0	0	0	0	0	0	16	0	0
448	0	0	0	0	0	0	0	2	0	0
449	0	0	0	1	0	0	0	24 5	0	0
453	0	0	0	0	1	0	0	9	0	0
458	1	0	0	0	0	0	0	6 5	0	0
463	0	0	0	0	0	0	0	17 5	0	0
468	0	0	0	0	0	0	0	4 5	0	0
469	0	0	0	0	0	0	0	34	0	0
480	0	0	0	0	0	1	0	26	0	0

Depth (cm)	*Parakıef fenella tnquetra type*	*Psectro cladıus (Psectrocl adıus)*	*Psectro cladıus (Allo & Meso)*	*Zalut schıa spB*	*Zalut schıa spA*	Pentaneu rını-undıf	*Procla dıus*	UK	UNID MISSING/ WORN	UNID INSTAR	SUM ALL HC	SUM IDed HC	Total CC
388	0	16 5	0	0 5	2	11	11	0	4	9	291 5	278 5	2
389	0	14 5	0	1	0	12	13	0	12 5	0 5	189	176	2
393	0	16 5	0	1	1	14 5	20	0	8 5	3 5	215	203	2
398	0	14 5	0	0 5	2 5	39	36	0	12	10	378 5	356 5	2 5
403	0	1 5	0	0	0	8	7	0	8	0	119	111	2
408	0	1 5	0	0	0	1	3	0	14	0	85 5	71 5	1
409	0	5 5	0	0	0	0	8	0	1 5	2	92 5	89	2 5
413	0	5	0	1	2 5	18	19 5	0	13 5	1 5	324 5	309 5	2 5
423	0	4	0	0	0	4	2	0	3	0	100 5	97 5	1
424	0	10 5	0	0	0	10 5	9	0	3 5	4 5	244 5	236 5	2
428	0	5	0	1	0	11	2 5	0	5	1	97 5	91 5	0 6
429	0	7 5	0	0	2	15 5	15	0	19	3	339 5	317 5	2
433	0	6 5	0	0 5	0	7	11 5	0	7	4	193	182	2
438	0	3	0	0	0 5	1	5	0	9 5	3 5	82	69	0 7
439	0	2 5	0	0	0	1	5	0	3	0 5	167	163 5	2
443	0	19	0	0	2	4 5	5	0	9 5	0	251	241 5	3
448	0	4	0	0 5	0	0	2	0	1 5	0 5	63	61	1 5
449	0	9	0	2	0	24	33	0	25 5	1 5	353 5	326 5	2
453	0	4 5	0	0	1 5	2	10	0	2 5	0 5	185	182	2
458	0	3	0	0 5	1 5	3 5	6	0	5 5	0 5	75 5	69 5	1
463	0	9	0	0	0 5	1	4	0	12	1 5	273	259 5	3
468	0	1 5	0	1 5	0	0	1	0	2	1	51 5	48 5	0 5
469	0	10	0	2	1 5	4 5	2	0	6 5	1	266	258 5	2
480	0	9	0	1	0 5	17 5	9	0	17	9	343 5	317 5	3