Lakes in the Far North of Ontario: Regional Comparisons and Contrasts

by

Josef MacLeod

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science (MSc) in Biology

Faculty of Graduate Studies
Laurentian University
Sudbury, Ontario

THESIS DEFENCE COMMITTEE/COMITÉ DE SOUTENANCE DE THÈSE

Laurentian Université/Université Laurentienne
Faculty of Graduate Studies/Faculté des études supérieures

Title of Thesis Titre de la thèse	LAKES IN THE FAR NORTH OF ONTARIO: REGIONAL COMPARISONS AND CONTRASTS
Name of Candidate Nom du candidat	MacLeod, Josef Charles
Degree Diplôme	Master of Science

Department/Program Département/Programme	Biology	Date of Defence Date de la soutenance	July 29, 2014

APPROVED/APPROUVÉ

Thesis Examiners/Examinateurs de thèse:

Mr. Wendel Keller
(Co-supervisor/Co-directeur de thèse)

Dr. John Gunn
(Co-supervisor/Co-directeur de thèse)

Dr. Richard Dyer
(Committee member/Membre du comité)

Dr. Andrew Patterson
(Committee member/Membre du comité)

Dr. Sarah Finkelstein
(External Examiner/Examinateur externe)

Approved for the School of Graduate Studies
Approuvé pour l'École des études supérieures
Dr. David Lesbarrères
M. David Lesbarrères
Acting Dean, Faculty of Graduate Studies
Doyen Intérimaire, Faculté des études supérieures

ACCESSIBILITY CLAUSE AND PERMISSION TO USE

Abstract

With the large scale of anticipated mining development in the Ring of Fire (ROF) area and the potential for other future industrial developments and rapid climate change in the north, there is a great need for basic limnological data for lakes in the Far North of Ontario. To address this need, water chemistry and crustacean zooplankton surveys of northern Ontario lakes were conducted to examine regional differences between lakes of the Precambrian Shield and Hudson Bay Lowlands, focusing on the ROF area, which straddles the boundary between these physiographic regions. Lakes of the ROF area displayed highly variable water chemistry, a product of the extensive peatland landscape with its mix of bog and fen watersheds. This peat cover appears to decouple, to varying degrees, the lakes from the influences of bedrock and surficial geology and is a source of complex organic matter and acids. Shield lakes in the western portion of our study area had base cation concentrations (Ca, Mg) markedly higher than those of previously studied Shield lakes south of 50°N, likely due to the abundance of lacustrine and glacial end-moraine deposits throughout western Ontario north of 50°N. The zooplankton species collected during this survey were generally similar to those reported for lakes further south on the Precambrian Shield. Zooplankton assemblages were strongly influenced by lake morphometry, with higher species richness in the deeper Shield lakes than in the shallower Lowlands lakes which would appear to offer less niche space for coexistence of species.

Acknowledgements

Many thanks to my supervisors, Bill Keller and John Gunn for supporting me through this whole process. I could not ask for better role models.

To my committee members, Andrew Paterson and Richard Dyer, thank you for your input and advice which steered me in the right direction with my writing many a time. Also, thank you to the Ontario Geological Survey (OGS), which provided data for the 2011 survey.

To my funding partners: The W. Garfield Weston Foundation, the Wildlife Conservation Society, The NSERC Canadian Network for Aquatic Ecosystem Services and The Canadian Wildlife Federation, a huge thank you to you all for supporting my project.

To Kim Armstrong and Jeff Amos from MNR, thank you for contributing data from the Broadscale Monitoring Program.

To Eabamatoong First Nation in Fort Hope and Xavier Sagutch, thank you for allowing me and my crew to work on your traditional lands and for helping plan out the field work.

To Adam Jeziorski and Kathryn Hargan at Queens University – thank you for your help in the field.

To Chantal Sarazin-Delay, thank you for your help in the field and for making all those maps for me.

To Lynne Whitty, many thanks for your work on my zooplankton data, advice and wonderful baking.

To all the other members of the Cooperative Freshwater Ecology Unit / Living with Lakes Centre at Laurentian University; John Bailey, Elizabeth Bamberger, Nathan Basiliko, Lorraine Brekke, Daniel Campbell, Michael Carson, Andrew Corston, Pete Cott, Kim Fram, Michelle Gillespie, Stacey Greene, Galen Guo, Lee Haslam, Jocelyne Heneberry, Vicky Jackson, Tom Johnston, Nadia Mykytczuk, Nicole Novodvorsky, Karen Oman, Caroline Sadlier, Erik Skokan-Emilson, Emily Smenderovac, Ashley Stasko, Lexi Sumner, Autumn Watkinson and Pete Whittington– Thank you for your advice, support and help with life, the universe and statistics.

To David Pearson and my film crew at Clearwater Studios; Laura Kendall, Chantelle Lafleur and Emily Nelson: many thanks for making my work look great.

To my dearest wife-to-be Kera. Thank you for opening up a wider world for me and for helping me through the tough times so we can build a bright future together.

To my Mom, Dad, family and friends, thank you for your support and advice all along the way and for not forgetting about me while I disseapeared into this project for nearly three years.

Many others who are too numerous to mention also have my gratitude so I will simply say you know who you are and thank you for all your help and support.

Table of Contents

List of Figures

List of Tables

List of Appendices

1 General Introduction

Currently there is a dearth of scientific knowledge about waters in the Far North of Ontario. As defined by the Ontario Ministry of Natural Resources (MNR) the Far North is an area of 452,000 km^2 located north of the managed forested zone of Ontario, beginning at approximately 50^0 N latitude (The Far North Science Advisory Panel, 2010). It is a vast area that includes the Hudson Bay Lowlands, the northwest portion of the Boreal Shield, 3 of Canada's largest river systems and a multitude of lakes (The Far North Science Advisory Panel, 2010).

As a result of its northern location, the presence of permafrost and the climatic regulation provided by Hudson Bay, which is gradually lessening, the Far North region appears to be particularly sensitive to the effects of global climate change (Gagnon and Gough, 2005). Far North Ontario lakes in permafrost areas are suspected to be sensitive because they are generally shallow and do not stratify thermally, which means they can quickly reach temperatures that may be intolerable to many aquatic life forms and have no thermal refuge available. Also, permafrost may act as a barrier to groundwater sources (Woo et al., 2000), isolating the surface wetlands from a key source of cool water replenishment and reducing the buffer against spiking water temperatures in response to rising temperatures. In addition to these lakes being vulnerable to the effects of global climate change, the particular region these lakes are located in is experiencing accelerated warming due to recent reductions in the duration and extent of ice cover on Hudson's Bay (Gough et al., 2004; Hochheim et al., 2011; Hochheim and Barber, 2014).

The chemistry of lakes is affected by atmospheric gases and contaminants, but also by terrestrial inputs. Along surface and groundwater flow-paths, minerals are leached from the soil and contributed to lakes (Livingstone, 1963). Thus, regional geomorphology, local geology and land cover influence the chemical makeup of inland lakes and also control the characteristics of drainage, nutrient inputs and flushing time (Wetzel, 2001). The study of landscape and surface landforms helps to understand the character of lakes and perhaps how future events may affect it. However, in the vast peatlands of the north, geological influences may be masked by the influence of extensive surface organic deposits.

Potential large-scale developments in parts of Ontario's Far North including mining activity, forestry operations, hydroelectric projects, and associated transportation corridors will affect the natural environment in this sensitive region in the near future. The Far North is also an area that is expected to see some of the greatest impacts from future climate change including permafrost melting, and changes to the length of the ice-covered season for lakes (The Far North Science Advisory Panel, 2010). These are just some of the threats that lakes and rivers will likely face in the future. To understand how northern waters might respond to such future impacts and how to best manage these resources to conserve aquatic ecosystem integrity requires an understanding of how aquatic ecosystems are structured at the present time.

As an early step in developing the scientific knowledge of northern aquatic systems, we conducted surveys to obtain basic information on habitat conditions (physical and chemical) and biological communities in a wide ranging set of northern boreal lakes.

Given the particular interest in potential mining development in the "Ring of Fire" area of north-western Ontario, we initiated surveys in this general area. Survey planning involved discussion with people from First Nations communities in the area.

Data from this research project will help advance long term conservation objectives and knowledge for the northern boreal region by:

- Characterizing aquatic ecosystem structure in an understudied area of Ontario's Far North/boreal area;
- Providing information to support the management and conservation of aquatic resources, including the assessment of the nutrient status of lakes that can be used in fisheries management;
- Providing background information from which to assess future ecological changes resulting from industry and climate change.

The overall goal is to improve the scientific understanding of lakes in the north, to allow better predictions of their sensitivity to future industrial development or changes in climate. This information will be shared with First Nations communities and all those involved in managing and protecting waters in the north. The Far North Act legislated First Nations involvement in the creation of community based land use plans. These data can help inform that process.

Chapter I of this thesis examines water chemistry, land cover and geology of the Ring of Fire area and surrounding landscape. Lake survey data collected at two widely different spatial scales were compared to determine if lake chemistry changed across the boundary between the Precambrian Shield and Hudson Bay Lowlands. One survey was in the immediate ROF area and the second covered a much broader span of Northern Ontario.

Chapter II documents the zooplankton species composition of lakes across northern Ontario. I examined patterns of changes in the presence and relative abundance of zooplankton species in relation to physical and chemical properties of lakes in the general ROF area, and compare the results with other lake surveys from Ontario.

The data gathered in this study provide a reference baseline for northern lakes that can be used in future environmental assessments. It advances our knowledge of aquatic ecosystem conditions in a mostly unstudied area, an area that is likely to see a great deal of both industrial activity and climate related changes in coming years. Developing our ability to predict how changes will impact this region will aid in adapting to and mitigating the effects of those changes. It is hoped that the documentation of current lake conditions provided here will aid in the development of such predictions.

2 Chemistry of Far North Lakes in Ontario: Regional Comparisons and Contrasts

2.1 Introduction

Conserving the diversity, function, and provision of aquatic ecosystem services in Ontario's northern boreal region in the face of future development and climate change requires sound scientific data from which to make informed management decisions. Ecosystem services, as defined in the UN Millennium Ecosystem Assessment (Hassan et al. 2005) are benefits people obtain from ecosystems, which are broken down into four types; provisioning services (food and water), regulating services (flood mitigation and disease regulation), supporting services (soil formation and carbon sequestration) and cultural services (recreation, spiritual or religious uses). Services from each of these categories are provided by the ecosystems of northern Ontario and must be accounted for when evaluating impacts from development in the region. Lakes in the Far North of Ontario are very vulnerable to future change. Climate forecasts suggest that climate warming will be most pronounced in northern areas of the province (Colombo et al., 2007). As well, future large-scale mining activity and associated infrastructure development is inevitable for the Far North of Ontario, with the discovery of massive metal deposits in Ontario's "Ring of Fire" (ROF) region. As the ROF is already undergoing unprecedented mineral resource exploration, it is critical to establish baseline water chemistry of lakes in this region so that informed management decisions can be made. With increasing interest in development throughout the north, and in the ROF in particular, there is a great need to improve our understanding of northern aquatic ecosystems so that we may understand how future impacts will affect this region.

The ROF straddles two seemingly dissimilar landscapes, the Hudson Bay Lowlands and the Precambrian Shield physiographic regions, which also encompass two ecozones, the Hudson Plains and the Boreal Shield, respectively. Although very different, both of these physiographic regions are home to a plethora of freshwater lakes which are a vital component of the health of northern environments. Yet despite this importance, a dearth of information exists on the basic water chemistry of these lakes.

A first step to understanding the current lake chemistry of these two landscapes is to understand their different geneses. Six thousand years ago the vast Tyrrell Sea began to recede across what is now the northern coast of Ontario on Hudson and James Bays, giving way to a dynamic coastal terrain composed of mineral wetlands, which eventually developed into vast organic peatlands that dominate the landscape today (Riley, 2011). The Hudson Bay Lowlands comprises large river systems and numerous lakes of varying sizes, with a peat-filled bog and fen landscape in between. It is an incredibly flat area, dropping by as little as 65-100 cm/km across the ~300 km span between Big Trout Lake and Hudson Bay (Riley, 2011). Isostatic rebound in this region is very high, with the land rising as much as 1.2 m/century (Webber et al., 1970) and the coast rising quicker than further inland, which is gradually reducing the already gentle slope. Lakes in this region are generally shallow, but may be very large in surface area with extensive littoral communities.

Surrounding the Lowlands to the south and west is Canada's Precambrian Shield. Covering half of Canada's landmass, it is composed of outcrops of granites and other igneous and metamorphic rocks that were formed approximately 3 billion years ago (Royal Commission on the Northern Environment, 1985). Between 63 and 570 million years before present, deposition within the Hudson Bay sedimentary basin resulted in the formation of a variety of rocks including shales, sandstones and limestones which lap onto the Canadian Shield (Johnson et al., 1991) and extend as far west as the ROF deposit area. The Shield has been scoured by glaciers many times before the last glaciation retreated ~10 000 years ago leaving behind a variety of glacial deposits and, in places, a fluted landscape. The glacial meltwater formed the massive glacial Lake Agassiz that eventually receeded into many smaller deep lakes (Leverington et al., 2002). Shield lakes are, in general, deep, cold, dilute and clear.

Currently the boundary between the Precambrian Shield and the Hudson Bay Lowlands is delineated on various maps in approximately the same location (Royal Commission on the Northern Environment, 1985; The Far North Science Advisory Panel, 2010; Riley, 2011). This region is covered by thick quaternary glacial deposits and peat creating a complex surficial landscape (Dyer and Handley, 2013) and making the delineation of the boundary very difficult. However, using satellite imagery available from Google Earth, a rather distinctive change is visually apparent across the survey region, changing from a striated north-south pattern in both the lake shapes and river drainage patterns in the west to a more featherlike, random orientation in the east. This change occurs abruptly, and a line drawn down this perceived contrast coincides very well with the boundary lines depicted in the maps and literature references described above. This apparent functional boundary delineation should then prove useful, for examining lake characteristics, at least at a coarse scale.

At this Shield/Lowland boundary lies the ROF, a geological formation of volcanic origin located in the interior of the Far North of Ontario. The headwaters of the Attawapiskat River, which is the largest river flowing through the region, are located on the Precambrian Shield, and flow off the Shield through the ROF area into the Lowlands and eventually into James Bay, 250 km to the east. The ROF is an area rich in mineral deposits including nickel, copper, zinc and chromite. These Ni-Cu-platinum group element deposits were first discovered by a mineral exploration program in 2007. Since then, mineral claims have greatly expanded in this region and assessments for a chromite mine are now underway.

With the ROF straddling the boundary between the Shield and the Lowlands, we would expect to find a contrast between lake chemistry reflective of the changes in the landscape and the flow of water as we move eastward from the Shield onto, and through, the Hudson Bay Lowlands. However, since this boundary has only been constructed using coarse data at a provincial scale, it is unknown if lake chemistry will clearly separate by ecozone, or if the boundary region itself will have unique properties, which may have implications for future management.

Surveys of lake chemistry were initiated in 2011 and 2012 to gather basic limnological data on lakes in the previously understudied regions of the ROF and northern Ontario. The overall goal of the study was to answer the following questions:

1) What are the limnological properties of lakes in the Far North of Ontario within and surrounding the ROF region and do they differ from lakes in other parts of Ontario?

2) Do patterns in lake chemistry within and surrounding the ROF correspond with known geological or other landscape features?

3) Is it possible to differentiate between Shield and Lowlands lakes by examining water chemistry within the ROF area, or across larger geographical areas of northern Ontario?

2.2 Study Sites

In August 2011, in collaboration with Laurentian University, 98 lakes (21 on the Shield, 77 on the Lowlands) were sampled by the Ontario Geological Survey (OGS) in the ROF area (Figure 2-1) (Dyer, 2011). Shield lakes were all within 10 km of the Shield/Lowlands boundary as defined by the Ontario Ministry of Natural Resources (The Far North Science Advisory Panel, 2010). Located 40-140 km east of the community of Webequie, the survey was centered on McFauld's Lake in the ROF area and extended 50 km to both the east and west. McFauld's Lake is the epicenter for mineral exploration activity in this region. This region's elevation ranges from 140-180 masl with very little (<5 m) relief. Discontinuous permafrost ranges from sporadic to widespread throughout the study region (Brown et al., 2002).

A second survey was performed in July 2012 by scientists at Laurentian and Queen's universities and sampled a smaller number of lakes (n = 29; 14 on the Shield and 15 on the Lowlands) across a much broader section of northern Ontario (Figure 2-1) overlapping with some of the ROF lakes in the 2011 study (n = 13). Also in summer 2012, the Ministry of Natural Resources (MNR) Broadscale Monitoring Program (BSM) sampled 20 lakes (16 Shield and 4 Lowlands) throughout the broader region of Northern Ontario which were added to the data set (total n=49, 30 on the Shield, 19 on the Lowlands, Figure 2-1).

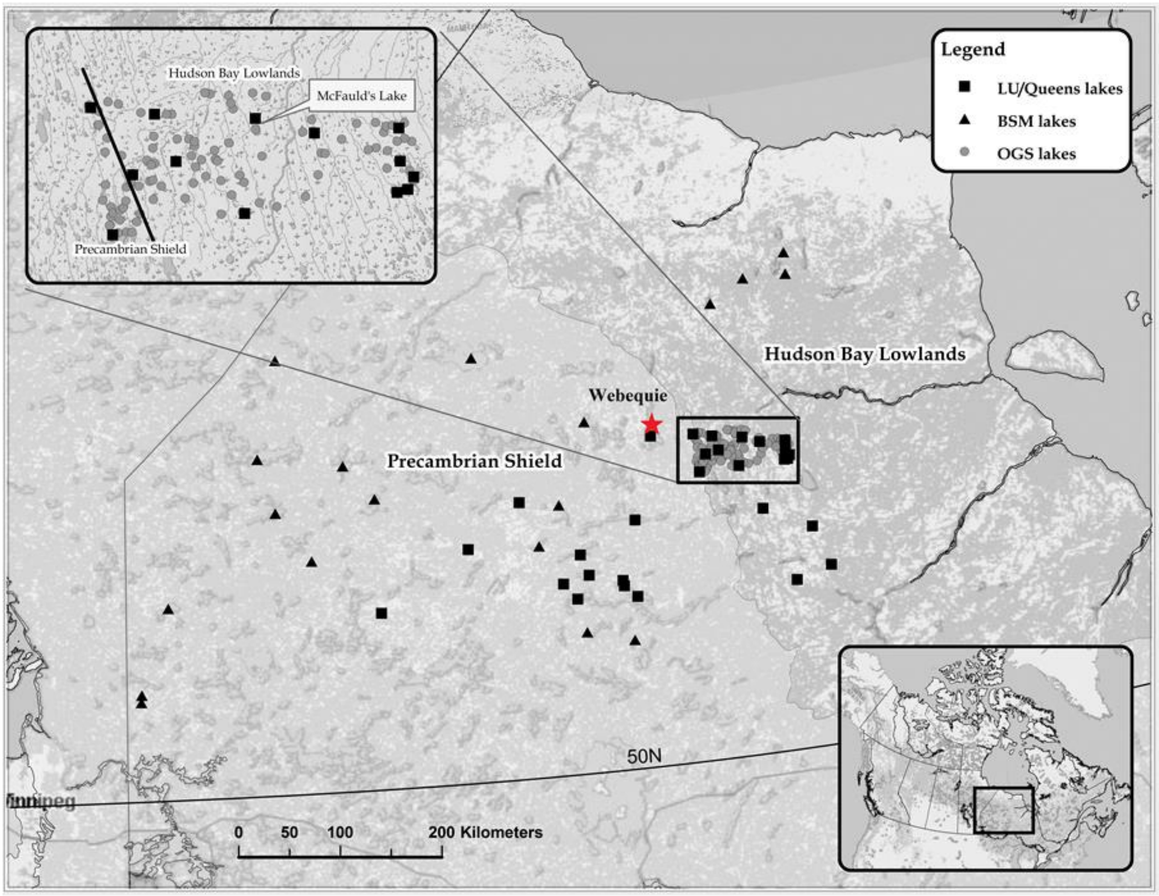

Figure 2-1: Map of Northern Ontario showing locations of survey lakes from 2011 (OGS), 2012 (LU/Queens) and 2012 (BSM). ROF Shield lakes were within 10 km of the Shield/Lowlands boundary.

2.3 Methods

2.3.1 ROF Sampling Protocol

Between August 13 and 15, 2011, single point water samples from 98 lakes in the ROF area were collected by OGS (Figure 2-1) following methods from Dyer (2011). The lakes spanned the estimated boundary of the Precambrian Shield and the Hudson Bay Lowlands. A helicopter on floats was used to travel to the lakes. Water samples for laboratory analyses were collected from a depth of 0.5-1.0 m by a weighted intake hose connected to a diaphragm pump inside the helicopter. Water quality parameters, including pH and conductivity, were measured at each lake site using a flow cell attached to a YSI model 600xl multi-parameter probe. Total phosphorus (TP), three measures of nitrogen (total Kjeldahl nitrogen, combined ammonia and ammonium, combined nitrate and nitrite), dissolved organic carbon (DOC) concentrations and true colour were analysed at the Ministry of the Environment's (MOE) laboratory in Dorset, Ontario. Metals and other parameters were analysed by the OGS geosciences laboratory in Sudbury, Ontario.

2.3.2 Niagara College GIS data overview

Wilson and Liu (2012) assembled a database of landscape vegetation characteristics of the region surrounding the lakes from the OGS survey. In total, 96 local catchment areas were delineated using ArcGIS, of which 63 contained at least one of the study lakes. Also, some catchments contained multiple lakes. Data from those 63 catchments were analysed with the chemistry data to identify relationships between lake chemistry and vegetation characteristics.

2.3.3 2012 Lake Survey (Laurentian/Queen's Universities)

From July 11-15, 2012, 29 lakes were sampled (Figure 2-1) by plane on amphibious floats. At each location lake depth and transparency (Secchi depth) were determined using a sonar depth sounder and Secchi disc, respectively. An oxygen and temperature profile was recorded with readings for every 1 m water depth until within 1 m of the bottom using a YSI model 52 oxygen meter.

A water sample was obtained at each lake using a composite depth sampling bottle. The device consisted of a large sealed bottle (~ 4 litre volume) with a metal handle and removable plastic cap. The cap had a 5 cm hole drilled into it allowing water to enter the sampler at a slow rate. The device was first rinsed with lake water before being secured to a rope and then lowered to the Secchi depth or 1 m off bottom (which ever was shallower) and then slowly retrieved allowing the bottle to fill with water evenly across all depths. Care was taken to ensure that the bottle was not full before resurfacing. The water in the sampler was then filtered through an 80 µm mesh Nalgene® funnel (funnel rinsed with surface water three times) to fill the final sample container (a large volume (6 L) jug). This process was repeated until the sample jug was full. Samples were stored in a cooler while in the field. At the end of each day the 6 L jugs of composite water samples were subsampled for each laboratory analysis, as appropriate. Sutey et al. (2011) describes the full set of bottles used for samples sent to the Dorset MOE Laboratory. Each of the sample bottles was rinsed three times with filtered water from the composite sampler before filling. These samples were packed in coolers with freeze-packs for transit back to Sudbury and subsequently Dorset for analysis.

2.3.4 Ontario Ministry of Natural Resources Broad Scale Monitoring survey

Encompassing the time window of the lake survey by Laurentian and Queen's Universities (July 11-15th 2012), the Ministry of Natural Resources (MNR) surveyed 20 lakes throughout Northwestern Ontario for zooplankton between June 14th to Aug 25th 2012. Water chemistry samples for most lakes were collected between May 14th and May 15th 2012. Spruce, Shamattawa, McFaulds, Wildberry and Pine lakes were sampled between July 19th and August 26th 2104. Comparable methods to the Laurentian/Queen's survey (above) were employed (Sandstrom et al., 2011). Samples were analysed at the Dorset MOE lab.

2.3.5 Data Screening and Combining

All 2012 water chemistry data (LU and BSM) were obtained from samples submitted to the Ontario Ministry of the Environment's Dorset Environmental Science Centre. Standardized methods and experienced personnel ensure quality, precision data. Detection limits for all parameters were more than adequate for the purposes of this survey's objectives. Physical data for lakes were re-checked for accuracy prior to analysis. All original data were kept on a series of un-altered, backed-up digital files, and only copies of these files were taken and manipulated for analysis. This ensured that at all stages it was possible to re-check any generated data sub-sets for accuracy against the original raw data.

2011 ROF data

Forty-six variables were measured initially (with levels above detection limits) : lake depth, temperature, specific conductivity, conductivity, resistivity, total dissolved solids, pH, true colour, DOC, nitrate and nitrite, ammonia and ammonium, total Kjeldahl nitrogen, TP, reactive silicate, ions (Ca, Cl, Fe, Fl, K, Mg, Na, PO_4, SO_4) and trace metals (Al, As, B, Ba, Bi, Ce, Cs, Eu, Ga, Gd, La, Mn, Nd, Pr, Rb, S, Sb, Si, Sm, Sr, Th, U, Y). However, most of the trace metals did not have values above detection limits in most or all of the lakes and were excluded. Total nitrogen was calculated (total N; mass sum of Kjeldahl N + nitrate and nitrite), along with inorganic nitrogen (inorganic N; mass sum of nitrate and nitrite + ammonium and ammonia). The resulting list of variables used in the analysis included sample depth, conductivity, pH, DOC, true colour, inorganic nitrogen (calculated), total N (calculated), TP, reactive silicate (Si), calcium (Ca), chloride (Cl), iron (Fe), potassium (K), magnesium (Mg) and sulphate (SO_4).

Landscape cover data from Niagara College were expressed as percentages for each of the 63 catchments containing sampled lakes which were delineated. The landscape variables measured were coniferous tree cover, broadleaf tree cover, mixed wood tree cover, shrub wetland cover, treed wetland cover, and open water. Additionally, this data set included lake areas for the OGS lakes.

2012 Laurentian/Queens and BSM (MNR) data

Data from the 2012 Laurentian/Queens survey were pooled with data from the BSM survey by MNR. Both surveys collected a composite sample using the same equipment and the same method of collection. Samples were analysed by the same laboratory at the MOE Dorset Environmental Science Centre. A nearly identical suite of nutrients, major ions and trace metals was measured, and a selection of variables was chosen which was present for both surveys, did not have values below detection limits, and are commonly used in northern limnological studies (Keller and Pitblado, 1984; Medeiros et al., 2012; Bos and Pellatt, 2012). These included the same set of variables as analysed for the 2011 survey as well as dissolved inorganic carbon (DIC). Also, lake length (maximum distance across the center of the lakes) was used instead of lake area because GIS data were not available for all lakes, and length was more easily and accurately measured using satellite maps from Google Earth. The result was two data sets: 98 lakes from 2011 and 49 lakes from 2012 with 13 lakes overlapping from the two sets (Figure 2-1). It should be noted that 13 lakes from the BSM survey were sampled in mid-May while the other lakes from both BSM and Laurentian were sampled in July/August. Differences between these two sampling times were assessed statistically, and were found to have not impacted the results.

2.3.6 Statistical Analysis

Software

IBM-SPSS v. 19 was used to obtain descriptive statistics on the data, to test for normality and to produce graphs of the distribution of data for each variable. These analyses were used to make decisions on data transformation. Spearman's correlation coefficients were also used to identify the basic patterns in the data and to identify where variables described overlapping variance (co-variates). This information was used to reduce the number of variables for further analysis. PRIMER-E v. 6.0 software was used to perform cluster analysis, Principle Components Analysis (PCA) and Analysis of Similarities (ANOSIM) tests.

2011 Survey

Lake depth, conductivity, TP, reactive silicate, Ca, Fe, Mg, Si, Cl and SO_4 were Log^{10} transformed to achieve the best fit to a normal distribution for analysis. Other variables (pH, DOC, true colour, total N, inorganic N, K) were left untransformed (transformation did not improve their distributions or, in the case of pH, was not appropriate since it is already log transformed). Descriptive statistics (mean, median, max, min, standard deviation) were generated for all variables. Mann-Whitney U-tests were used on all the variables to identify where differences existed between the means of the Shield and Lowlands lake groups.

Cluster analysis was used to group the lakes by the similarity of their chemical properties without any *a priori* expectations. For the 2011 data, attempts were made *a posteriori* to visually match the groups formed from cluster analysis to known anomalies such as gabbro rock outcrops and eskers.

Correlation analyses were run between all chemistry/ lake morphometry variables. When running multiple correlations, a more stringent significance criterion is necessary. Typically, a sequential Bonferroni adjustment is used. However, this method has a number of problems when applied to ecological data (Moran, 2003) , so, as a compromise, an α criterion level of 0.01 was used instead of 0.05 to account for increased error from multiple correlations without being so conservative that it would eliminate all correlations from significance. A second set of correlations was run between these variables and the landscape cover variables generated by Niagara College, recorded as % land cover. For this analysis, the same criterion for significance was used, but only 63 lakes were entered (i.e., one for each watershed) to avoid duplication of data. Where watersheds had more than one lake delineated, the largest lake was chosen.

Principle Components Analysis (PCA) on standardized data was used to illustrate dominant patterns using a multivariate approach. PCA is a commonly used tool in environmental studies (see Keller and Pitblado, 1989; Keller and Conlon, 1994; Medeiros et al., 2012). By plotting the individual lake scores for the first two principle components, a two dimensional representation of each lake's chemical properties was obtained. The lakes were then labeled by physiographic region using the selected Shield/Lowlands boundary to illustrate the relationship to the landscape. There are 21 lakes within 10 km west of this line in the data set, referred to as 'Shield lakes'. The other 77 lakes in the study were assumed to be 'Lowlands' lakes. Several techniques were used to contrast these subsets of Shield lakes and Lowlands lakes in the data set.

When testing the significance of differences between lakes using a multivariate method, a common difficulty arises of meeting parametric test assumptions which are often too stringent for ecological data. Non-parametric permutation tests provide a powerful and effective solution (Clarke, 1993; Anderson, 2001). Analysis of Similarities or ANOSIM has been used before to test data related to spatial differences (Oliver and Beattie, 1996; Chapman and Underwood, 1999). It is used here for a multivariate test of differences between lake groups due to its ability to analyse data which do not meet the assumptions of homogeneity of variances and normal distribution of data. ANOSIM calculates a Global R statistic, which represents the degree to which the similarities between the groups being tested are greater than the similarities within those groups, similar to the F ratio in ANOVA. ANOSIM then shuffles the data, generates new randomly assigned groups, and recalculates the global R statistic between the randomly generated groupings. The shuffling process is repeated, recalculating R as many times as specified by the user (in this case 999 times, which is the amount needed to produce a significance level or $p < 0.001$ or 0.1%). ANOSIM then compares the R statistic generated from the original data groupings to the distribution of all the R statistics from the 999 reshufflings and calculates the significance level (p) for the observed R (the likelihood that this R could have come from this distribution of Rs). If the sample group's R lies far enough outside of this distribution (using a similar criterion of $p < 0.05$ as in parametric tests), then the null hypothesis can be rejected indicating that the R calculated from the observed data is likely to have come from this distribution.

2012 Survey

DIC, conductivity, alkalinity, TP, reactive silicate, Ca, Cl, Fe, Mg, K, Na and SO_4 were all Log^{10} transformed, which resulted in a more normal distribution of data. The other variables were left untransformed. Descriptive statistics were calculated for all variables. Mann-Whitney U-tests were used on all the variables to identify where differences existed between the means of the Shield and Lowlands lake groups.

Statistical approaches used were similar to those used for the 2011 data. Cluster analysis, which searches for natural groupings within data (Everitt, 1974), was used to show how the chemistry of the lakes grouped without any *a priori* notions. Correlation analysis was used to identify groups of variables with strong covariance. Due to the large number of correlations and the possibility of inflated error levels (as well as to retain enough of the data as to be a robust analysis), a criterion for significance of $p < 0.01$ was used. Additional correlations were performed using only Shield Lakes from 2012 to further characterize lake groups. PCA was used to produce a simpler set of lake chemistry parameters and then plot the lakes by these components to illustrate relative similarities between lakes. PCA was chosen due to its ability to reduce large numbers of data variables into a simplified model which can illustrate groupings easily. Analysis of Similarities (ANOSIM) was used to differentiate Shield from Lowlands lakes for 2012. A further principle components analysis was performed using data for other northern Ontario lakes from Keller and Pitblado (1989); Paterson et al. (2014); and Keller (2010 unpublished data). The surveys used in the combined analysis (i.e., Laurentian/Queens and BSM (2012), northwestern lakes from Keller and Pitblado (1989), northern lakes from Paterson et al. (2014) and Keller (2010 unpublished data) were selected because together they include lakes which extend from the most southwest portion of northern Ontario (Shield lakes) through to the Lowlands lakes farthest to the northeast near Hudson Bay. This covers the regions to the south west, east and north of the 2012 surveys, resulting in a lake set that includes most of northern Ontario above Lake Superior.

2.4 Results

2011 Ring of Fire (ROF) Survey

General patterns in lake chemistry were described using descriptive statistics. Despite all lakes in the survey being shallow (≤ 5m max depth), they showed highly diverse water chemistry characteristics. Conductivity (7-161 µs/cm), true colour (13.6-195.0 TCU), inorganic N (6-156 µg/L), reactive silicate (0.02-2.36 mg/L), Ca (0.48-28.07 mg/L), Fe

(0.01-1.13 mg/L) and Mg (0.19-5.05 mg/L) all showed more than an order of magnitude difference between maximum and minimum values (Table 2-1).

Table 2-1: Descriptive statistics of lake chemistry and morphometry from the 2011 survey (n=98, 77 Lowlands and 21 Shield).

Variable	Mann-Whitney U-test significance (p)	Region	Mean	Median	Max	Min	Standard Deviation	Coefficient of Variation
Lake Depth (m)	**0.029**	**Lowland**	**1.82**	**1.50**	**5.00**	**0.50**	**0.87**	**0.48**
		Shield	**1.39**	**1.30**	**2.50**	**0.90**	**0.42**	**0.30**
Lake Area (ha)	**0.880**	**Lowland**	**95.01**	**32.00**	**1081.71**	**5.09**	**184.08**	**1.94**
		Shield	**90.89**	**29.84**	**738.16**	**9.31**	**167.96**	**1.85**
Conductivity (μs/cm)	**0.060**	**Lowland**	**41.55**	**34.00**	**161.00**	**7.00**	**31.05**	**0.75**
		Shield	**45.95**	**45.00**	**79.00**	**19.00**	**15.59**	**0.34**
pH	**0.004**	**Lowland**	**7.26***	**6.97**	**8.28**	**4.24**	**-**	**-**
		Shield	**7.44***	**7.26**	**8.10**	**6.75**	**-**	**-**
DOC (mg/L)	**0.143**	**Lowland**	**14.63**	**14.10**	**24.40**	**5.60**	**3.69**	**0.25**
		Shield	**15.54**	**15.60**	**19.00**	**12.00**	**1.91**	**0.12**
True Colour (TCU)	**0.140**	**Lowland**	**81.63**	**79.80**	**195.00**	**13.60**	**37.43**	**0.46**
		Shield	**67.87**	**72.60**	**111.00**	**15.80**	**23.55**	**0.35**
Inorganic N (μg/L)	**0.496**	**Lowland**	**46.03**	**40.00**	**156.00**	**6.00**	**20.68**	**0.45**
		Shield	**48.00**	**48.00**	**80.00**	**26.00**	**15.86**	**0.33**
Total N (μg/L)	**0.000**	**Lowland**	**447.56**	**434.00**	**703.00**	**254.00**	**95.62**	**0.21**
		Shield	**526.29**	**504.00**	**711.00**	**417.00**	**75.76**	**0.14**
Total P (μg/L)	**0.109**	**Lowland**	**17.02**	**14.30**	**44.40**	**7.20**	**7.58**	**0.44**
		Shield	**14.13**	**12.30**	**27.90**	**4.80**	**5.69**	**0.40**
Reactive Si (mg/L)	**0.004**	**Lowland**	**0.58**	**0.44**	**2.36**	**0.02**	**0.56**	**0.95**
		Shield	**0.95**	**0.98**	**2.00**	**0.12**	**0.56**	**0.59**
Ca (mg/L)	**0.099**	**Lowland**	**7.60**	**6.47**	**28.07**	**0.48**	**5.78**	**0.76**
		Shield	**8.32**	**8.56**	**14.16**	**3.00**	**2.89**	**0.35**
Cl (mg/L)	**0.758**	**Lowland**	**0.19**	**0.15**	**1.25**	**0.02**	**0.17**	**0.86**
		Shield	**0.16**	**0.15**	**0.26**	**0.05**	**0.05**	**0.34**
Fe (mg/L)	**0.049**	**Lowland**	**0.10**	**0.07**	**1.13**	**0.01**	**0.14**	**1.35**
		Shield	**0.06**	**0.05**	**0.14**	**0.01**	**0.04**	**0.62**
K (mg/L)	**0.007**	**Lowland**	**0.15**	**0.15**	**0.25**	**0.04**	**0.03**	**0.22**
		Shield	**0.18**	**0.17**	**0.33**	**0.11**	**0.05**	**0.26**
Mg (mg/L)	**0.028**	**Lowland**	**1.21**	**1.02**	**5.05**	**0.19**	**0.90**	**0.74**
		Shield	**1.42**	**1.39**	**2.32**	**0.55**	**0.44**	**0.31**
SO_4 (mg/L)	**0.731**	**Lowland**	**0.15**	**0.08**	**1.51**	**0.03**	**0.21**	**1.40**
		Shield	**0.23**	**0.08**	**2.01**	**0.03**	**0.46**	**2.01**

* pH mean was calculated by averaging the $[H^+]$ ion concentrations and then converting that value to pH.

Correlation analyses of chemistry and morphometry variables characterized the general physico-chemical patterns within the 2011 lakes, revealing several strong associations between variables. pH, major ions and conductivity were most closely associated (Table 2-2). Lake depth was inversely correlated with most chemistry variables, whereas lake area showed negative correlations with DOC and true colour, but positive correlations with pH, TP, conductivity and Ca (Table 2-2). Some relationships emerged which were unexpected, including pH correlating positively with total N ($r = 0.350$) and reactive silicate ($r = 0.342$).

Further correlation analyses on 63 lakes (one for each watershed) between chemistry and vegetation cover variables characterized how chemistry related to the land cover. This showed only a small number of significant correlations (Table 2-3). Total N correlated positively with mixed wood forest cover ($r = 0.338$), which was highest in the west. pH increased as wetland cover decreased and as mixed wood cover increased to the west ($r = -0.393$), reflecting a progression from open wetland landscape to more abundant tree cover in the west.

Within the five clusters that were differentiated by cluster analysis, there were no discernible patterns relating to actual spatial orientation across the study region or with respect to known surface water influences from eskers or gabbro rock outcrops. The clusters were composed of 1-3 randomly situated lakes which separated from all the others at differing levels of resemblance.

Table 2-2: Correlation analysis of 2011 morphometry and chemistry variables (n=98, 77 Lowlands and 21 Shield). Variable associations which did not meet the criterion of p <0.01 Spearman's correlations were omitted.

	LakeLength	Conductivity	pH	DOC	Truecolour	NTOT	NINORG	Phosphorus	ReacSilicon	Al	Ca	Fe	K	Mg
LakeDepth				-.400	-.580	-.533	-.276		-.400					-.273
LakeArea	.879	.351	.468	-.513	-.461			.297			.330			
LakeLength		.320	.430	-.481	-.451						.309	-.306		
Conductivity			.805		-.284				.641	-.622	.986		.417	.958
pH					-.522	.300	.336		.408	-.527	.775	-.282	.486	.757
Truecolour							-.259				-.276			
DOC					.702	.500			.558			.527		
NTOT							.478		.385					
NINORG								.510				-.324	.286	
ReacSilicon										-.401	.639	.272		.690
Al											-.637			-.591
Ca													.395	.962
Fe														
K														.412

Table 2-3: Spearman Correlation analysis of land cover and water chemistry using one lake for each of the 63 catchments identified by Niagara College (p<0.01, r values shown).

	Mixwood Forest Cover	Wetland Tree Cover	Open Water Area
LakeArea			.796
LakeLength			.729
pH		-.393	
DOC			-.355
NTOT	.338		
K		-.376	

Principle components analysis (PCA) illustrated that the Shield and Lowlands lake groups overlapped to a considerable degree, with the Shield lakes displaying a densely clustered, less variable group within a more diverse assortment of Lowlands lakes (Figure 2-2). The lakes oriented along axes which generally corresponded with pH/ major ions and clarity/DOC respectively. The variables which loaded most highly positively on principle component one (36 % of variation explained) were Mg (0.426), Ca (0.420), conductivity (0.417) and pH (0.393) while principle component two (19.5% of variation explained) had high positive loadings for true colour (0.537), DOC (0.523) and Fe (0.486) (Figure 2-3, Appendix A). Total P loaded negatively on PC2 (-0.167).

The Analysis of Similarities (ANOSIM) test of the 2011 data (Shield lakes vs. Lowlands lakes), performed to test the significance of differences between the two groups, showed no difference (global R = -0.068 p = 0.845). The negative value of the observed R in 2011 indicates that there is a greater similarity between the two groups than there is within each group (Chapman and Underwood 1999). This reflects the fact that the Lowlands group had very high variability, encompassing the variability of the Shield group.

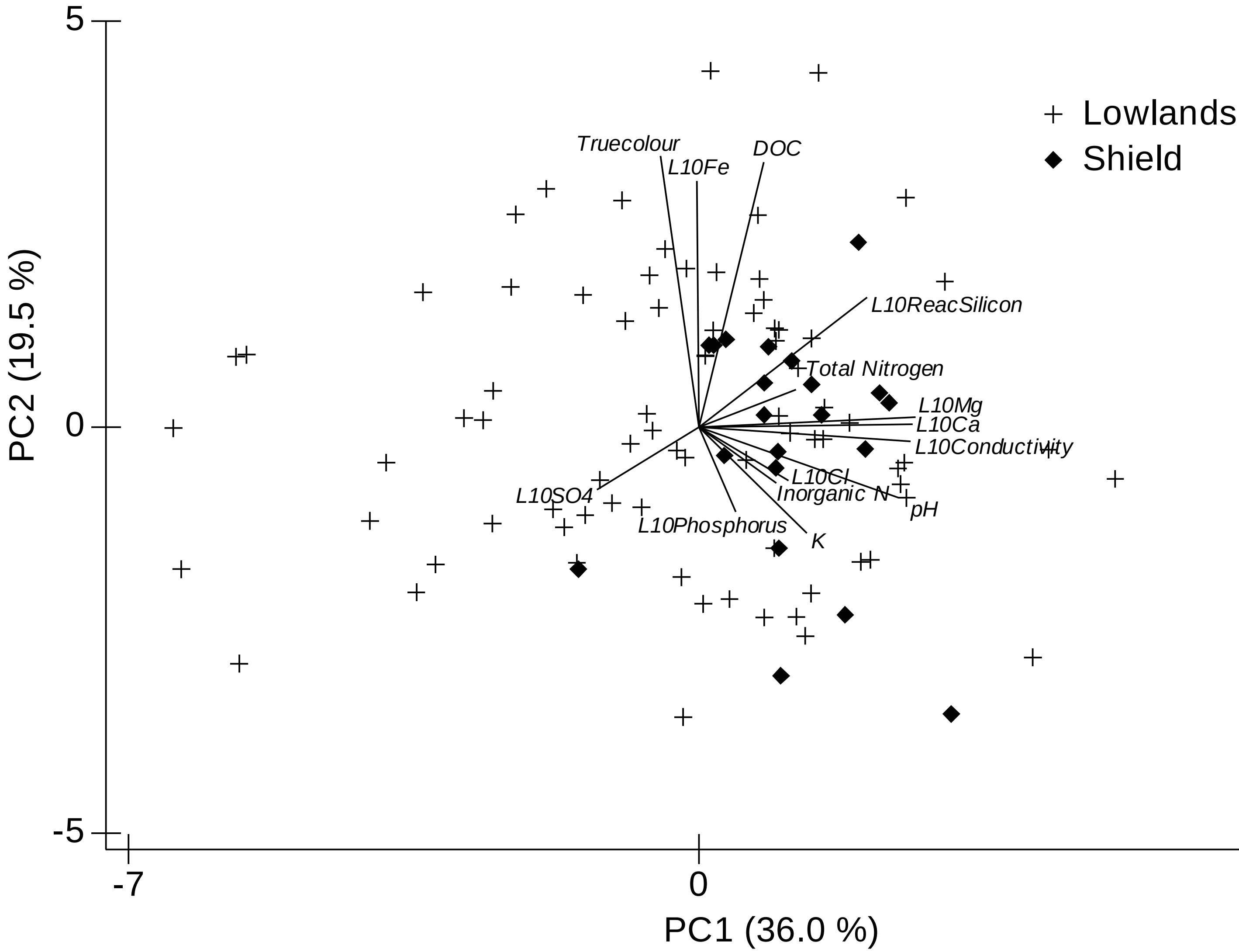

Figure 2-2: PCA of 2011 chemistry variables from the ROF. % of variation explained indicated on axes (n = 98, 21 Shield and 77 Lowlands).

2012 Survey

These lakes showed a much larger range in depths than those sampled in 2011 (Coefficient of variation of 1.17 - 1.19 in 2012, 0.3 - 0.48 in 2011, Table 2-1, 2-4). Similar to the 2011 data, there were large (order of magnitude) ranges between maximum and minimum values in conductivity (21.2-232 µs/cm), true colour (5.2-155.0 TCU), Inorganic N (3.6-53.4 µg/L), Al (1.8-238 mg/L), Ca (2.16-34.9 mg/L), Fe (0.01-1.43 mg/L), Mg (0.48-7.92 mg/L), reactive silicate (0.02-2.0 mg/L), K (0.09-1.04 mg/L), and SO_4 (0.05-1.9 mg/L) (Table 2-4). Lowlands lakes had shallower depths, smaller areas, lower pH, conductivity and major ions (K, Mg SO_4) and higher DOC, true colour and TP (Mann-Whitney U-tests, $p<0.01$) than Shield lakes. In the 2012 survey Ca, K, Mg and SO_4 concentrations as well as conductivity, pH, DIC and reactive silicate were significantly higher in the Shield lakes than in the Lowlands lakes (Mann-Whitney U-tests, $p<0.01$). Conversely, DOC, true colour, total N, TP and Fe were higher in lakes within the Lowlands.

Spearman correlation coefficients between chemistry variables which were significant ($p<0.01$) are shown in Table 2-5. Alkalinity, conductivity, pH, Ca and Mg were all inter-correlated. DOC correlated with true colour and both were inversely correlated with DIC.

Additional analyses using only 2012 Shield lakes showed that Longitude correlated negatively with pH, conductivity, Ca and Mg. Conductivity correlated positively with both pH and major ions (Ca, Mg, K). Within the Lowlands lakes, Latitude correlated positively with Cl, true colour with DOC, conductivity with pH, Ca, Cl, Mg and K. pH correlated with conductivity, Ca, Mg and K.

Table 2-4: Descriptive statistics of lake chemistry and morphometry from the 2012 survey (n=49, 19 Lowlands and 30 Shield).

Variable	Mann-Whitney U-test significance (p)	Region	Mean	Median	Max	Min	Standard Deviation	Coefficient of Variation
Lake Depth (m)	0.000	Lowland	3.43	1.90	16.00	1.20	4.09	1.19
		Shield	14.17	7.00	70.00	1.80	16.64	1.17
Lake Area (ha)	0.000	Lowland	1047.77	498.78	5061.70	35.78	1231.57	1.18
		Shield	8181.94	2303.62	62566.00	309.00	14474.00	1.77
Conductivity (µs/cm)	0.007	Lowland	61.73	51.00	137.00	21.20	34.95	0.57
		Shield	89.65	82.00	232.00	25.40	46.68	0.52
pH	0.000	Lowland	7.5*	7.43	7.93	6.94	-	-
		Shield	7.84*	7.77	8.25	7.17	-	-
DOC (mg/L)	0.000	Lowland	13.50	13.30	18.60	7.80	2.90	0.21
		Shield	10.12	11.15	15.40	4.90	2.79	0.28
DIC (mg/L)	0.003	Lowland	6.03	4.72	14.10	1.62	3.83	0.64
		Shield	9.70	8.55	29.70	1.94	5.79	0.60
True Colour (TCU)	0.000	Lowland	86.02	83.00	155.00	31.00	34.16	0.40
		Shield	43.51	41.10	127.00	5.20	28.29	0.65
Inorganic N (µg/L)	0.194	Lowland	15.36	15.60	25.20	8.00	5.32	0.35
		Shield	12.54	9.95	53.40	3.60	10.05	0.80
Total N (µg/L)	0.029	Lowland	391.05	384.00	513.00	297.00	63.48	0.16
		Shield	350.50	355.50	540.00	163.00	77.51	0.22
Total P (µg/L)	0.005	Lowland	15.36	15.60	25.20	8.00	5.32	0.35
		Shield	12.54	9.95	53.40	3.60	10.05	0.80
Reactive Si (mg/L)	0.000	Lowland	0.33	0.26	1.46	0.02	0.34	1.03
		Shield	1.02	0.92	2.00	0.02	0.57	0.56
Ca (mg/L)	0.024	Lowland	10.14	7.80	28.30	3.14	6.78	0.67
		Shield	12.92	12.25	34.90	2.16	7.47	0.58
Cl (mg/L)	0.505	Lowland	0.56	0.22	2.45	0.11	0.72	1.29
		Shield	0.30	0.24	1.11	0.10	0.23	0.77
Fe (mg/L)	0.000	Lowland	0.20	0.14	0.51	0.06	0.15	0.75
		Shield	0.15	0.08	1.43	0.01	0.28	1.87
K (mg/L)	0.000	Lowland	0.16	0.15	0.26	0.09	0.04	0.25
		Shield	0.49	0.43	1.04	0.18	0.21	0.43
Mg (mg/L)	0.000	Lowland	1.44	1.27	2.81	0.48	0.74	0.51
		Shield	2.79	2.61	7.92	0.93	1.59	0.57
SO_4 (mg/L)	0.000	Lowland	0.17	0.15	0.35	0.05	0.08	0.47
		Shield	0.65	0.53	1.90	0.10	0.48	0.73

* pH mean was calculated by averaging the [H^+] ion concentrations and then converting that value to pH

Table 2-5: Spearman correlation matrix (r values) of water chemistry from 2012 surveys (n=49, 19 Lowlands and 30 Shield). Variable associations which did not meet the criterion of p <0.01 Spearman's correlations were omitted.

	Area	Log10DIC	DOC	Log10Conductivity	Log10TotAlkalinity	pH	Truecolour	NTotal	Log10PTOT	Log10Ca	L10Cl	Log10Mg	Log10K	Log10Si	Log10Na	Log10Sulfate	Log10Fe
Depth	.527	.427	-.651	.427	.375	.498	-.582	-.464	-.405	.375	.392	.487	.640	.629	.393	.670	-.369
Area		.452		.458	.407	.523				.414		.587	.594	.539	.369	.464	
Log10DIC			-.384	.994	.966	.904	-.472			.986	.363	.939	.455	.646	.372		
DOC						-.531	.915	.606	.462			-.371	-.601			-.617	.632
Log10Conductivity					.963	.886	-.430			.993	.386	.942	.442	.665	.392		
Log10TotAlkalinity						.835	-.383			.971		.915	.392	.616			
pH							-.592			.852		.916	.642	.627		.367	
Truecolour								.481	.478	-.388		-.430	-.577			-.492	.681
NTotal									.595				-.396	-.369		-.552	.475
Log10PTOT																	.662
Log10Ca											.377	.917	.364	.631			
Log10Mg													.626	.747	.346	.374	
Log10K														.636	.418	.782	
Log10Si															.382	.552	
Log10Sulfate																	-.448

Principle components analysis (PCA) characterized broad-scale patterns and identified the primary sources of chemistry variability among the 2012 lakes. The variables which loaded most highly on principle component one were Mg (0.332), pH (0.329), DIC (0.324) and conductivity (0.322). The variables which loaded most positively on principle component two were Fe (0.373) and DOC (0.313) while SO_4 (-0.356) loaded negatively (Figure 2-3, Appendix B). Total P also loaded positively on PC2 (0.293).

Differences between sampling times were assessed in two ways. First, a subgroup was selected of the 13 lakes sampled in mid-May. Since these were all Shield lakes, I selected the 13 most northerly Shield lakes (to match latitude) from the lakes sampled in July. ANOSIM was run using all chemistry variables to test for differences between May and July sampled lakes. No difference was found (ANOSIM global $r = -0.006$, $p = 0.466$). Then, to test for specific differences, I ran independent samples t–tests between the two sample time groups for each of the chemistry variables. Only two differences were found: DOC was lower in the May sampled lakes ($p < 0.01$, means: 9.0mg/L for May (range 5.5-12.5mg/L), 11.4mg/L for July (4.9-15.4mg/L)) and Na was higher in May ($p <0.01$, means: 0.77mg/L for May (range 0.44-1.45mg/L), 0.54mg/L for July (0.42-0.90)). In both cases, the ranges overlapped between groups. May DOC levels, which were an important variable for the second axis of the PCA in figure 2-3, fell entirely within the range of the July DOC values and Na was not a strongly loading variable at all. Therefore, it appears that the effects of the sampling time difference would not impact the outcome of the PCA in figure 2-3.

The two lake groups show much clearer separation in 2012 than in the 2011 survey (Figure 2-3). Lowlands lakes showed lower scores on PC1 and higher scores on PC2 than Shield lakes, with little overlap between groups. Interestingly, Goods Lake and Leaver Lake, which were the only two lakes also sampled in 2011 from the Shield group, fell within the region occupied by Lowlands lakes. The principle components analysis clearly illustrates how the two groups displayed little overlap in their distribution; the only two lakes from the Shield group which overlapped with the Lowlands lakes are within 10 km of the boundary.

The Analysis of Similarities (ANOSIM) test of the 2012 data (Shield lakes vs. Lowlands lakes), which was performed to test the significance of differences between the two groups showed a very significant difference (global $R = 0.375$, $p < 0.001$) between Shield and Lowlands lakes. Taking a cross section of lakes from similar latitudes (52-53°N), the differences in character between the Shield and Lowlands for selected variables are visually apparent (Figure 2-4).

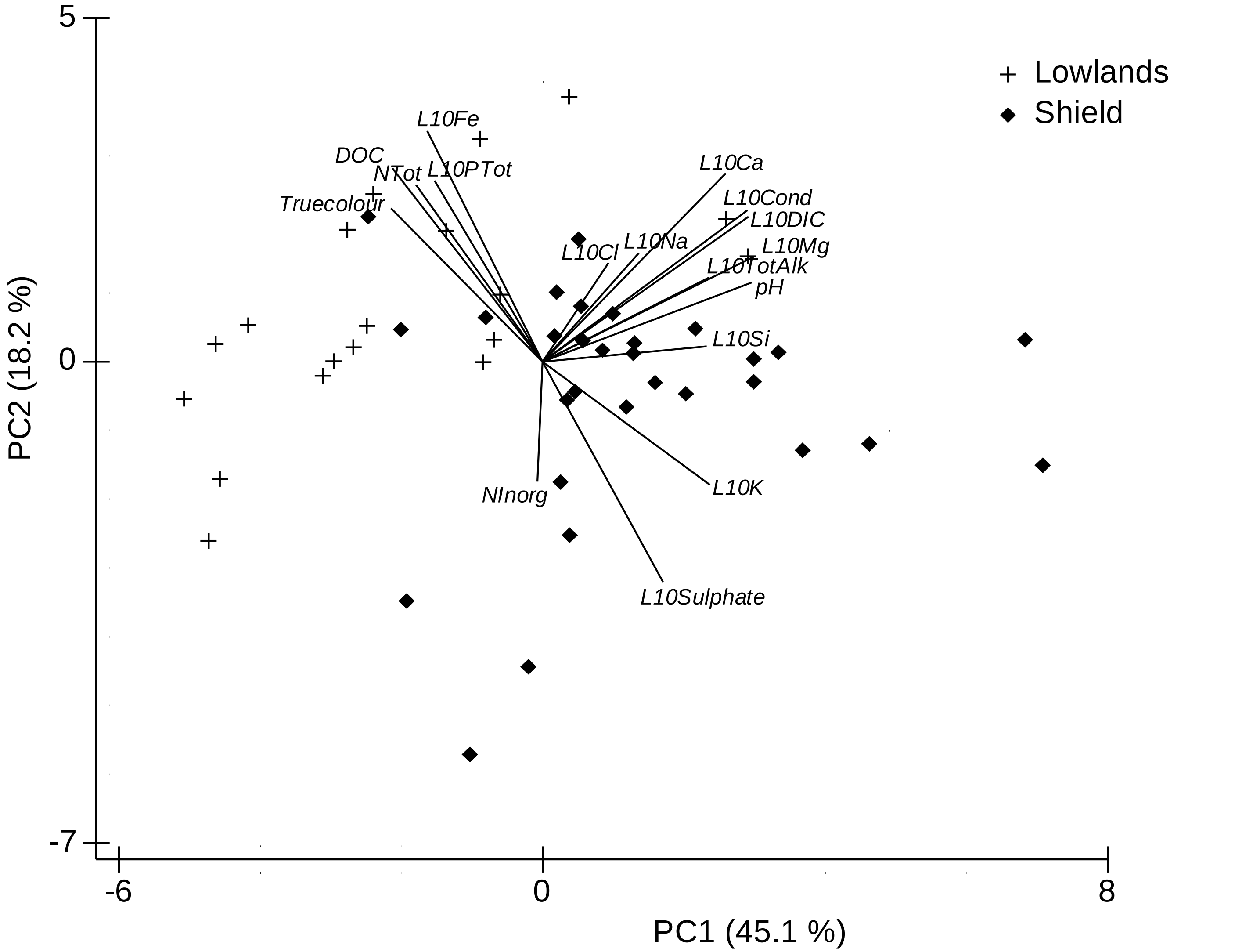

Figure 2-3: PCA of chemistry variables from 2012 survey (n = 49, 30 Shield and 19 Lowlands).

Annual variation in water chemistry did not appear to be an important confounding factor affecting the interpretation of lake chemistry patterns. Variations of chemical properties of the 13 lakes overlapping the two surveys (2011 and 2012) between years, illustrated a similar pattern in both years for major ions and nutrients (Figure 2-6). Testing with analysis of variance (ANOVA) revealed significant differences between years for only TP ($F = 10.62$, $df = 25$, $p < 0.01$) and Iron ($F = 8.972$, $df = 25$, $p<0.01$).

Analysis by PCA of the combined data (Laurentian/Queens and BSM (2012, northwestern lakes from Keller and Pitblado (1989), northern lakes from Paterson et al. (2014) and Keller (2010 unpublished data)) showed clear regional separation (Figure 2-6). The variables which loaded highest on principle component one were Ca (0.346), conductivity (0.333), alkalinity (0.333), latitude (0.324) and pH (0.321), while the variables which loaded highest on principle component two were K (0.460), lake depth (0.379), Na (0.372), lake area (0.327), and Mg (0.313) (Figure 2-6). Unfortunately, variables related to clarity (DOC, true colour) were not available for comparison across all lake sets, and so could not be entered into the analysis.

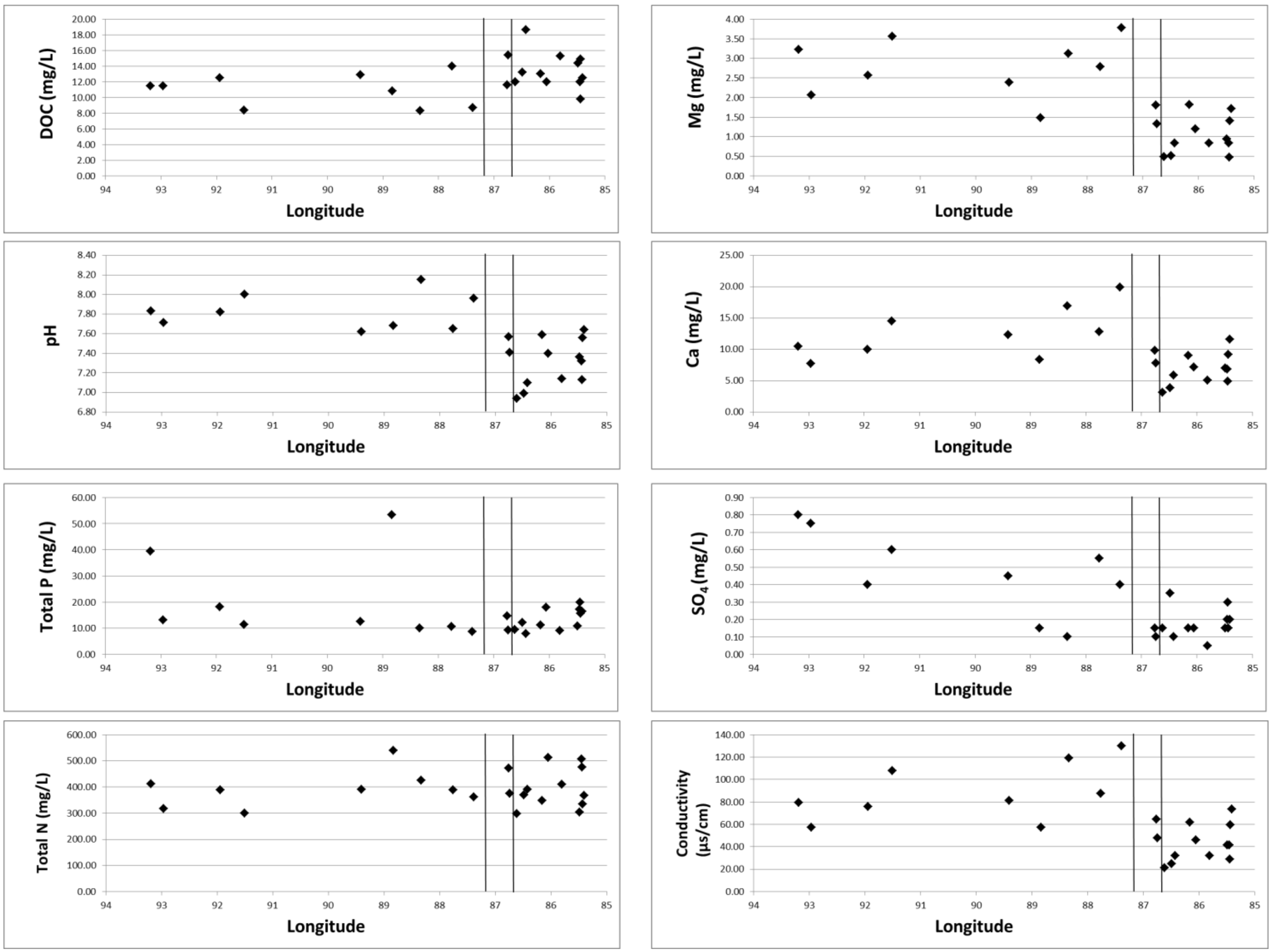

Figure 2-4: Chemical properties of selected lakes (2012 survey lakes between ~52°-53° N latitude) plotted by longitude. The estimated Boundary region between the Hudson Bay Lowlands and the Precambrian Shield is indicated by the vertical black lines.

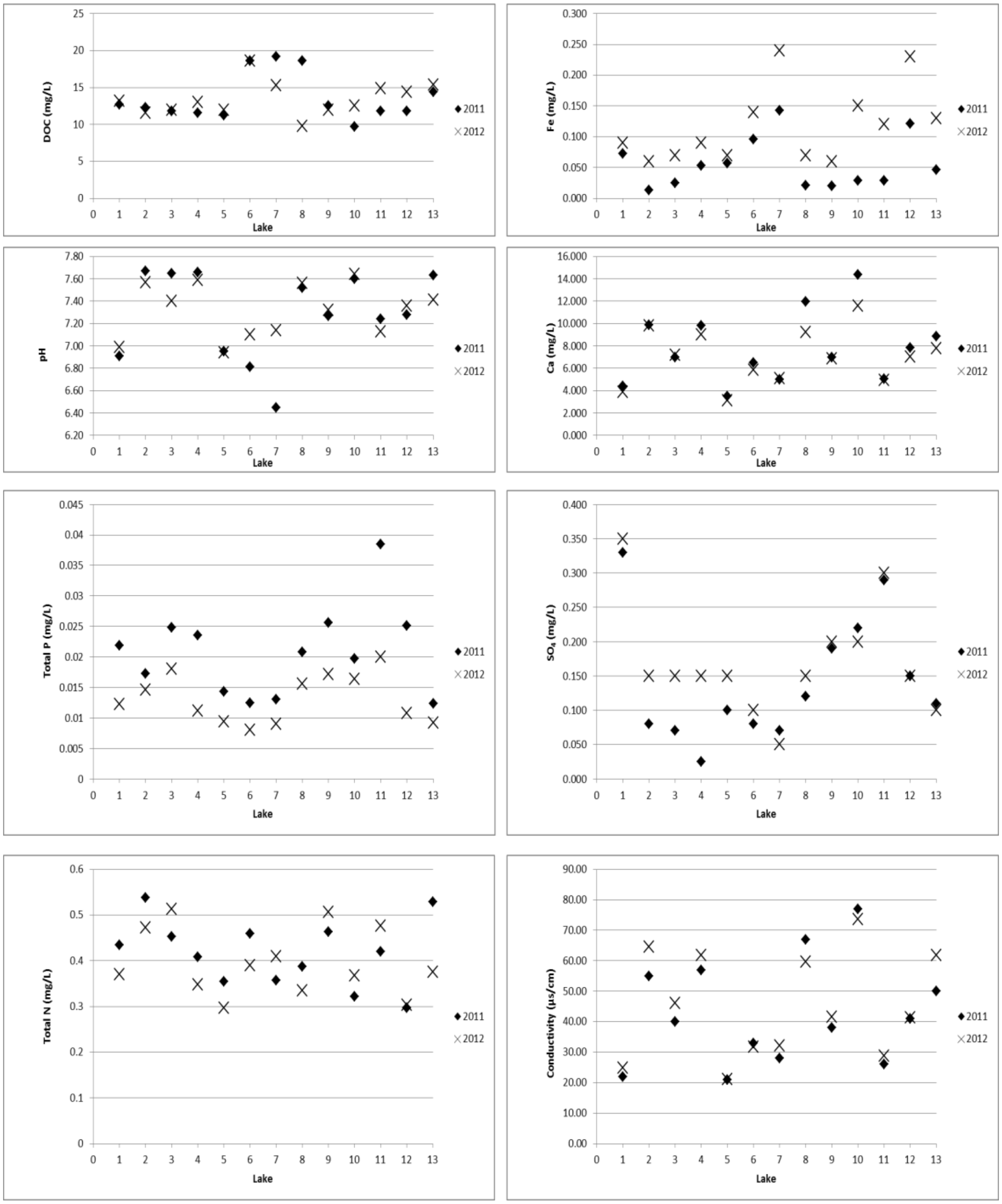

Figure 2-5: Temporal comparison of selected chemical variables for 13 lakes overlapping between 2011 and 2012 surveys.

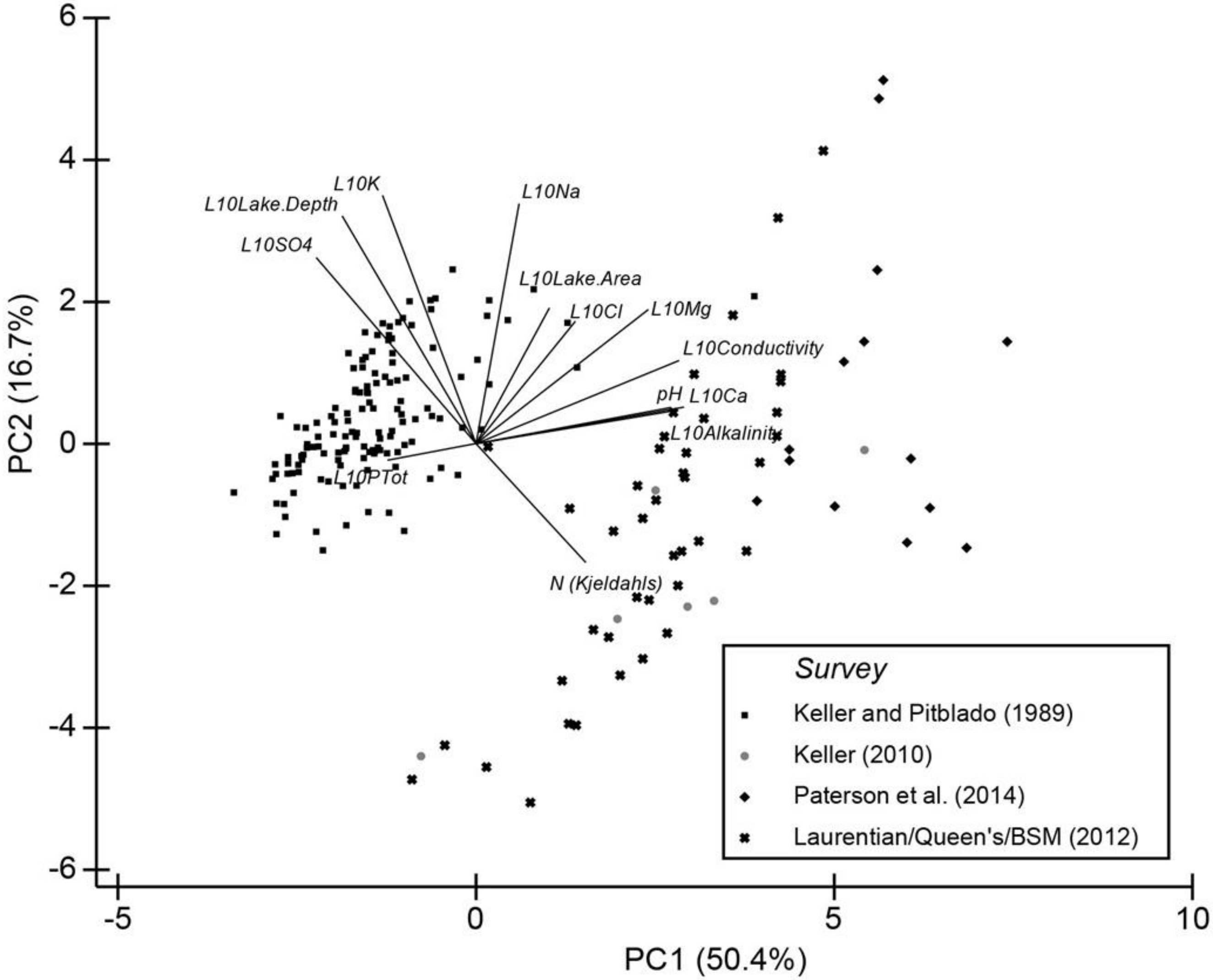

Figure 2-6: PCA of chemistry variables from multiple surveys (Laurentian/Queen's/BSM (2012), Keller and Pitblado (1989), Paterson et al. (2014) and Keller (2010)) across Ontario. Only lakes from Keller and Pitblado (1989) were located south of 50°N.

2.5 Discussion

2.5.1 Variability in Lake Chemistry

The lakes of the ROF region displayed comparatively high variability considering that the 2011 survey only covered an area of 95 x 45 km. By contrast, the 2012 survey covered an area which is 72 times larger (740 km x 420 km). It is also worth noting that the lakes in the ROF survey (2011) were all shallow (<5 m deep) but ranged in size from ~5 ha up to over 1000 ha (Table 2-1). These lakes have proportionately larger littoral habitats and may be more productive than deeper lakes due to the increased percentage of sunlight penetration per lake volume. Many chemical variables (pH, conductivity, Total N, Si, Ca, Mg, SO_4) actually varied more within the ROF region than across the much broader 2012 survey (Table 2-1, Table 2-4). Variation in both surveys was primarily driven by ionic strength (pH, conductivity, Ca and Mg) and secondly by clarity and organic content (true colour and DOC).

To put this variability in context, the ROF lakes span the majority of the pH range obtained from nearly 6000 Ontario lakes surveyed in the 1980s (Neary et al., 1990) (n = 5982, pH = 3.0-9.8). Compared with other parameters from Neary et al. (1990) including DOC (0.1-58 mg/L, n=2581), Ca (0.1-70.6 mg/L, n=3702), Mg (0.5-23.7 mg/L, n=3591), K (0.04-2.98 mg/L, n=3153) and SO_4 (0.3-34.5 mg/L, n=3599) the 98 ROF lakes covered roughly half of the range obtained for DOC and Ca, and a smaller (<20%) portion of the ranges of Mg, K, and SO_4 (Table 2-1). Nitrogen levels (especially inorganic N) were generally much lower than those reported in lakes from Neary et al. (1990). Clearly, lake chemistry varies widely within the ROF region.

Several factors likely contribute to the large lake chemistry variability seen in the comparatively small sample area of the 2011 survey. Lakes in the ROF region are part of a complex ecosystem which experiences fluctuations in temperature, wind and other climate factors daily, monthly and over the year. Lake responses to these variations will depend on the morphometry, hydrological connectivity and watershed characteristics of individual lakes. It is possible that the measured chemical properties were affected by evaporative enrichment considering the shallow depths of the lakes and timing of the survey (mid-July), which is when this effect is most prominent (White et al., 2014). Due to their shallow nature, these lakes would be expected to respond more rapidly to such external forces than deeper lakes. Peat layer thickness varies greatly throughout the study region (Lacelle, 1997; Tarnocai, 1997) and inputs of ions and particulates to these aquatic systems from rainfall and the vast wetlands surrounding these lakes will vary (Schindler et al., 1976; Pierson and Taylor, 1985).

Permafrost may also drive variability in lake chemistry within the ROF region. The 2011 study is located across a zone where permafrost extent varies considerably, from no permafrost to a few (<10%) isolated patches, becoming more prevalent north and eastward to a moderate (as much as 50%), but sporadic discontinuous distribution (Heginbottom et al., 1995), which increases in the direction of the climatic influence of Hudson Bay. The extensive peat overburden in this region (Tarnocai, 1997), acts as a conduction pathway for groundwater (Devito et al., 1996). When combined with a range of differing permafrost densities throughout this region (Heginbottom et al., 1995), a fluctuating permeable/impermeable barrier is created. This may isolate flow between water bodies, much like water bodies on a floodplain system with temporary linkages to each. This may allow lakes to diverge chemically as the flow of nutrients and organic matter is restricted by stagnant hydrologic conditions that isolate the lakes and then change again when connections are re-established through rainfall events that promote subsurface flow (Stieglitz et al., 2003). This may be further accentuated by melting permafrost as a result of warming from climatic change (Anisimov and Nelson, 1996; Osterkamp and Romanovsky, 1999), which would open up new hydrological connections as it melts. The ever-changing nature of the hydrologic landscape promotes divergence (Stieglitz et al., 2003), which may account for much of the high variability observed in lake chemistry in the ROF region. Detailed data on the exact thickness and extent of permafrost surrounding each lake would be needed to determine the degree to which this explains the observed variability of the regional lake chemistry.

Considering the large degree of variation in lake chemistry within the ROF region (Table 2-1), and given that changes in geological characteristics are not mirrored in any obvious changes in lake chemistry across the region it seems that lake chemistry is largely decoupled from reactions with bedrock and surficial geology by peatland cover. Extensive organic deposits present throughout this region appear to effectively isolate lakes and their catchments from the bedrock and glacial till. Carbon storage intensity is extremely high in the ROF (Lacelle, 1997; Tarnocai, 1997), which corresponds with the thick layer of peat. With relatively few rocky outcrops, the peat becomes the predominant landscape feature influencing lake chemistry. The minerals and nutrients from the sediments of the ancient sea-floor of the Lowlands, deposits of glacial till, and the bedrock are isolated by the peat and prevented from reaching these lakes. However, this isolation is not uniform, and will vary as localized surficial deposits interact with ground water where the peat layer is thin providing chemical influences. This is further complicated by the patchwork of bogs and fens which are present throughout this landscape (Barnett et al., 2013). Fens, which have groundwater connectivity can transport elements from subsurface till into lakes through their runoff. Bogs are, by definition, isolated from groundwater inputs, and therefore would be disconnected from surficial geology influences and instead provide increased organic carbon to lakes. Differences in the proportions of these different wetland types in different lake watersheds will affect ion concentrations, acidity and organic matter, contributing to chemically diverse lakes. This variability, and a general landscape dominance by peatlands appears to continue further west of the boundary with the Shield, and likely explains the lack of differences between Shield and Lowlands lakes in the 2011 survey.

2.5.2 Relationships between vegetative land cover and water chemistry

Terrestrial inputs of organic matter from plants are a significant source of DOC in many aquatic ecosystems (Wetzel, 2001). Changes to the cover and composition of plant communities across the landscape should therefore influence the chemical makeup of the lakes. However, few significant relationships were identified by analysing inter-relationships between land cover characteristics and lake chemistry. Wetland cover and peatlands, which generate organic acids (Sjors, 1959; Heinselman, 1963; Riley 2011), are denser in the eastern portion of the survey, which may explain the lower pH in the eastern lakes. Beyond this broad trend, the detailed catchment data needed to discern the interplay between the landscape and water chemistry were not available for this part of the province.

2.5.3 Differentiating between regional lake chemistry characteristics

Shield and Lowlands lakes within the spatially smaller ROF survey region had similar chemical characteristics. Positions of lakes in the two-dimensional ordination space generated by principle components analysis supported this finding as there was no clear separation between Shield and Lowlands lakes (Figure 2-3). The lakes fell along a continuum with the Shield lakes being located entirely within the confines of the ordination space occupied by Lowlands lakes. However, some variable-specific differences did exist. For example, Lowlands lakes displayed significantly lower pH, total N, reactive silicate and K than Shield lakes (Table 2-1). True colour was inversely correlated with pH and positively correlated to DOC. Thus the more acidic lakes in the survey were also highly coloured with higher organic matter, which is characteristic of dystrophic lakes that receive large amounts of their organic matter supply from allochthonous sources (Wetzel, 2001), in this case, peatland runoff.

In contrast to lakes in the ROF area, the lakes in the broader 2012 survey did show a clear separation between Shield and Lowland lakes (ANOSIM $p < 0.001$). Shield lakes are typically deep, cold and clear. The 2012 Shield lakes exhibited these general characteristics in that they had lower DOC, true colour and TP, which also indicates that they are less productive than the 2012 Lowlands lakes. The Shield lakes from 2012 had a deeper range of depths, which would alter how these lakes are affected by external forces such as solar radiation, which could in turn, affect thermal characteristics and lake chemistry.

Peatland cover also differed to a larger degree between Shield and Lowlands lakes in the 2012 survey. Peatlands were much less prevalent across the 2012 Shield lakes than in the 2012 Lowlands lakes (Tarnocai, 1997). Thus, the potential influence of organic acid inputs and isolation as a result of thick peat overburden, which varied considerably throughout the 2011 ROF survey area, was much reduced for Shield lakes located further west.

Conductivity, Ca and Cl were generally lower in both the ROF (mean values: conductivity: 42.49 µs/cm, Ca: 7.75 mg/L, Cl: 0.18 mg/L) and the broader Far North (mean values: conductivity: 78.82 µs/cm, Ca: 11.84 mg/L, Cl: 0.4 mg/L) than reported levels from other surveys conducted further north in subarctic Manitoba (Bos and Pellatt, 2012: mean values: conductivity: 310 µs/cm, Ca: 26 mg/L , Cl: 55.61 mg/L), and subarctic Ontario (Paterson et al., 2014): mean values: conductivity: 154.5 µs/cm, Ca: 25.1, Cl:4.6). The PCA in Figure 2-7 shows that lakes north of 50°N were generally higher in PC1 scores, which relates to higher ion strength and pH. Lakes from Paterson et al. (2014) also separated from the other lakes north of 50°N, possibly in part because chloride ions increase in closer proximity to Hudson's Bay.

2.5.4 Shield lake chemistry

The chemical properties of the 2012 Shield lakes stood out in several ways. All the lakes in the surveys north of 50°N separated from northwestern Ontario lakes (Keller and

Pitblado, 1989) which were all south of 50°N (Figure 2-7). In the 2012 survey, Shield lakes were differentiated primarily by a gradient of ionic strength and acidity (conductivity, Ca, Mg and pH). This group of lakes showed high Ca and Mg concentrations (mean values: conductivity - 89.65 µs/cm, Ca – 12.92 mg/L, Mg – 2.79 mg/L, Table 2-4). In fact, Ca and Mg ion concentrations and conductivity in the 2012 Shield lakes were much higher than those of most Shield lakes surveyed to date from south of 50°N in Ontario (Armstrong and Schindler, 1971; Keller and Pitblado, 1989; Keller and Conlon, 1994; Kurek et al., 2011; Palmer and Yan, 2013) (Figure 2-8). Kruskal-Wallis tests of chemistry variables confirmed that differences between the 2012 Shield lakes and Shield lakes from Keller and Pitblado (1989) were statistically significant (Table 2-6).

Northern Shield lakes (>50°N latitude) appear to be of a different character than most other Shield lakes. A likely explanation for these differences is the presence of extensive glacial end moraine and lacustrine deposits left during the end of the last ice age, which are more prevalent on the Precambrian Shield in the northwest region of Ontario above 50°N, (Royal Commission on the Northern Environment, 1985). Newer maps also confirm this (Four Rivers Matawa Environmental Services Group, 2013). The findings discussed here suggest that expectations for Shield lake chemistry must be expanded to include higher ionic strengths, higher TP concentrations and high variability in Shield lakes north of 50ºN.

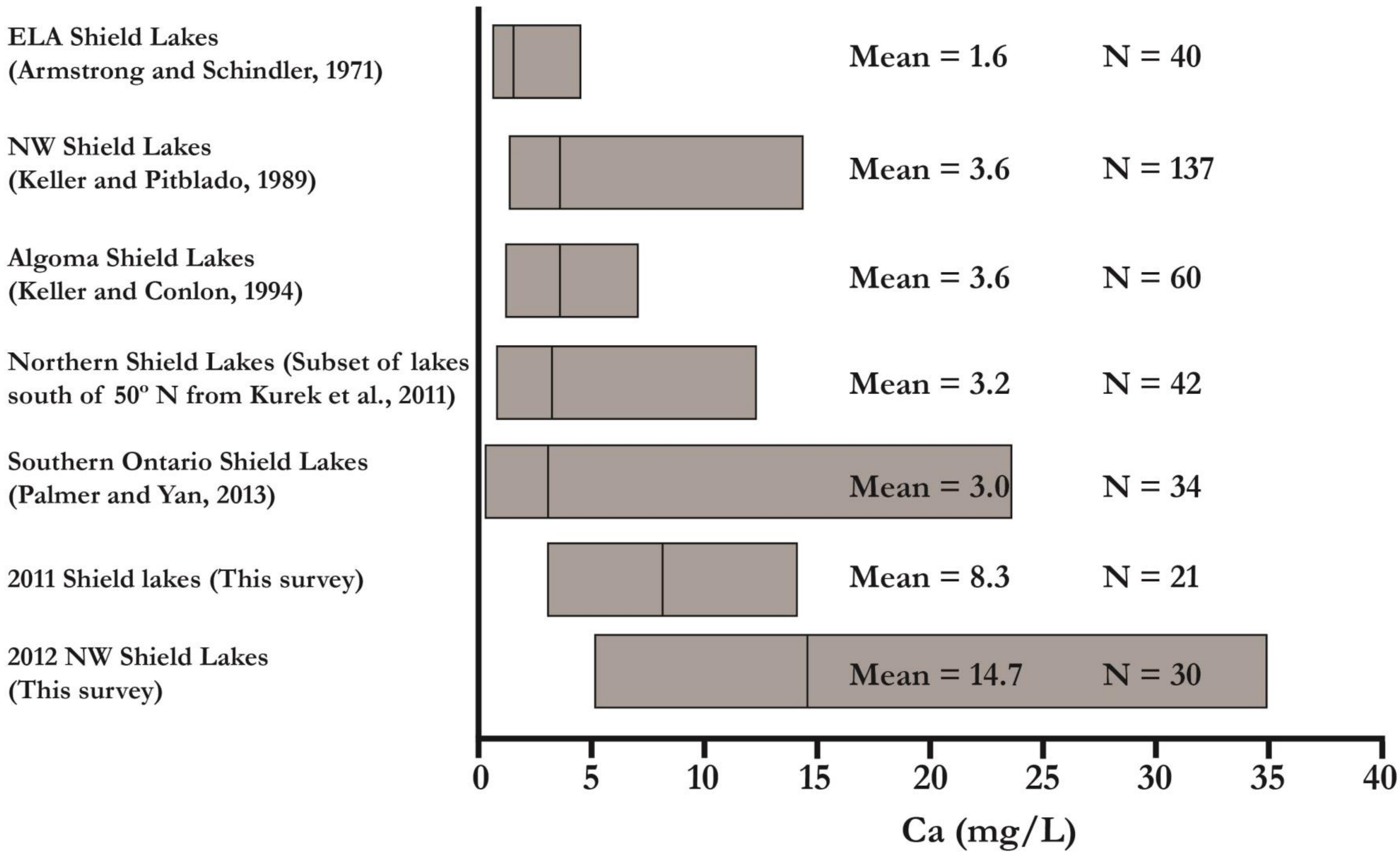

Figure 2-7: Comparison of Ca ranges with means for eight Shield lake surveys across Ontario.

Table 2-6: Comparison of the ranges of chemistry variables of Shield lakes from Keller and Pitblado (1989) and LU/Queen's/BSM (2012) (1981 n=137, 2012 n = 30). All variables were significantly different based on the result of the Kruskal-Wallis test for differences between means ($p<0.01$).

	Keller and Pitblado (1989)	LU/Queen's/BSM (2012)
Depth (m)	19.1(2.7-31)	10.01 (1.2-70.0)
Area (ha)	1127.7 (35-25390)	5415.63 (36-62566)
Latitude (degrees)	48.881 (48.083-50.35)	52.49 (51.14-54.33)
Longitude (degrees)	91.928 (89.083-94.683)	87.40 (85.14-92.86)
Conductivity (µs/cm)	33 (21-116)	89.65 (25.4-232)
Alkalinity (mg/L as $CaCO_3$)	8.0 (1.8-47.3)	40.59 (7.96-110)
Ca (mg/L)	3.6 (1.4-14.3)	12.92 (2.16-34.9)
Mg (mg/L)	1.2 (0.8-4.3)	2.79 (0.93-7.92)
Cl (mg/L)	0.527 (0.2-4.4)	0.41 (0.1-2.45)
Na (mg/L)	1.0 (0.6-2.8)	0.65 (0.41-1.45)
K (mg/L)	1.5 (0.2-4.4)	0.49 (0.18-1.04)
SO_4 (mg/L)	3.7 (1.9-6.7)	0.65 (0.1-1.9)
Total P (mg/L)	9 (2-36)	12.95 (3.6-53.4)
pH	6.84 (6.07-7.75)	7.63 (6.94-8.25)

2.6 Conclusions

Analysis showed that within the ROF region, the chemical distinction between Shield lakes and Lowlands lakes was not clear, and that by geographically expanding the study, the differences between these two regions did become apparent. In the ROF region lake chemistry appears to be largely decoupled from surficial geology by extensive, but variable peat deposits. This leads to variable influences from glacial till and lacustrine deposits that are determined by the variable nature of the wetland drainage (i.e. isolated bog runoff providing more organic matter vs. groundwater from fens providing ion sources). These factors contribute to highly variable local water chemistry. This is a first step towards understanding the differences and similarities between lakes along the boundary between the Hudson Bay Lowlands and the Precambrian Shield and particularly of lakes in the ROF region. In both surveys, lakes existed along a continuum formed of multiple characteristics despite very little overlap on the PCA in 2012.

Notably, this study identified differences between the chemical properties of Shield lakes in the Far North and Shield lakes elsewhere in Ontario, which expands the current understanding of Shield lake chemistry in a fundamental way. The existing perception of Shield lakes in Ontario must be broadened to include lakes which are comparatively high in Ca and Mg ionic strength, TP as well as alkalinity and conductivity. "Shield" lakes near the Shield/Lowlands transition are uncharacteristically shallow and highly coloured. It is hoped that the results presented here will aid in the development of monitoring programs and help further the scientific understanding of the potential sensitivity of northern aquatic ecosystems to multiple stressors.

2.7 Recommendations

This study has provided a baseline set of water chemistry data for lakes in a remote and understudied area of Ontario which will be facing increased pressure from future development. To date, this is the first published study to provide a limnological characterization of lakes in the ROF region. Lakes in the ROF region are highly chemically diverse and future monitoring programs will be challenged to account for this variability through adequate sampling programs across relatively small spatial scales. Multiple reference points chosen with care will be needed to ensure that environmental changes are adequately captured. Future studies will need to obtain more localized data on the watershed characteristics of individual lakes, including surrounding soil and wetland characteristics, water inflows and outflows and depth to bedrock in order to isolate meaningful small – scale patterns in lake chemistry. This has implications for future research and monitoring programs that will be developed for this region. Lake sampling will have to avoid assumptions of similarities between lakes across small distances and examine local influences on water chemistry on a lake by lake basis. Multi-lake sampling will be preferable to choosing a limited number of representative lakes for regions or size classes.

Considering the high costs of operating in these remote regions, taking advantage of passive data collection methods (temperature data loggers, automated samplers, etc..) is advisable. Also, making use of local knowledge and developing functional partnerships with local residents to increase and improve data collection would greatly improve the effectiveness of field research in the ROF.

3 Zooplankton of Far North Lakes in Ontario: Regional Comparisons and Contrasts

3.1 Introduction

The characteristics of crustacean zooplankton communities in lakes of the Far North of Ontario are relatively unknown. To date only two studies have examined patterns of zooplankton distribution and abundance in this vast region. Keller and Pitblado (1989) examined zooplankton communities in 39 lakes across the arctic watershed of Ontario. Paterson et al. (2014) sampled 17 lakes in the Hawley Lake/Sutton River region of the Hudson Bay Lowlands. The present analysis builds on that previous work by examining zooplankton communities in 41 lakes of the Far North of Ontario, particularly focusing on lakes in the general “Ring of Fire” (ROF) region of northwestern Ontario. The discovery of massive metal deposits in the ROF region has stimulated great interest for future mining development. As a consequence, basic ecological research to establish current conditions is critically needed for this region.

Zooplankton are a valuable component of aquatic ecosystems because they occupy central positions in aquatic food webs. They may play multiple roles within the energy flow system of a lake (i.e. larger predators as well as smaller phytoplankton grazers, Thorp and Covich, 1991), transferring energy to higher level organisms. Also, the relationships between many zooplankton species and specific lake characteristics have been well studied (e.g. Keller and Pitblado, 1989; Pinel-Alloul et al., 1990; Thorp and Covich, 1991; Palmer and Yan, 2013), which makes them valuable as indicator organisms for assessing environmental change (Valois et al., 2010; Jeppesen et al., 2011).

Zooplankton species occurrence in a given body of water depends on four general factors: 1) zoogeographical region 2) physical and chemical requirements of the species 3) availability of compatible food and 4) presence of predators (Leavitt et al., 1989; Thorp and Covich, 1991; Hessen et al., 2006; Adrian et al., 2009). Examining patterns of occurrence and abundance of communities provides a more robust tool to characterize a habitat than do assessments of a single species (Sprules, 1977). Thus, I employ multivariate analyses to examine relationships between zooplankton assemblages and water chemistry and physical characteristics. Analyses were conducted at two scales 1) across my 41 study lakes, and 2) across northwestern Ontario, using my lakes and other lakes available from the literature. Specifically I address the following questions: 1) what patterns of correlation exist between zooplankton species richness, species occurrence, and species relative abundances and lake physico-chemical characteristics in the Far North of Ontario? 2) Are there differences in the crustacean zooplankton communities of lakes in the Hudson Bay Lowlands (Hudson Plains Ecozone) and the Precambrian Shield (Boreal Shield Ecozone)?

3.2 Study Sites

In July 2012, Laurentian and Queen's Universities collaborated to sample 29 lakes across a section of northern Ontario including the ROF area (Figure 3-1). Within the study area, the boundary between the Hudson Bay Lowlands and the Precambrian Shield was nominally defined using the existing Ontario Ministry of Natural Resources (MNR) map boundary, such that there were 14 Shield lakes and 15 lakes on the Lowlands. There is great uncertainty associated with the positioning of this boundary because factors such as the thickness of peat and glacial till overburden vary widely, resulting in a variable transitional landscape. Also, in summer of 2012, the MNR's Broad Scale Monitoring Program (BSM) sampled zooplankton for 12 lakes (8 Shield, 4 Lowlands) throughout the broader region of Northwestern Ontario which were added to the data set (Figure 3-1). In total, 41 lakes were sampled, 22 lakes were located on the Shield and 19 were on the Lowlands. These included a wide range of lake sizes and depths (Figure 3-1).

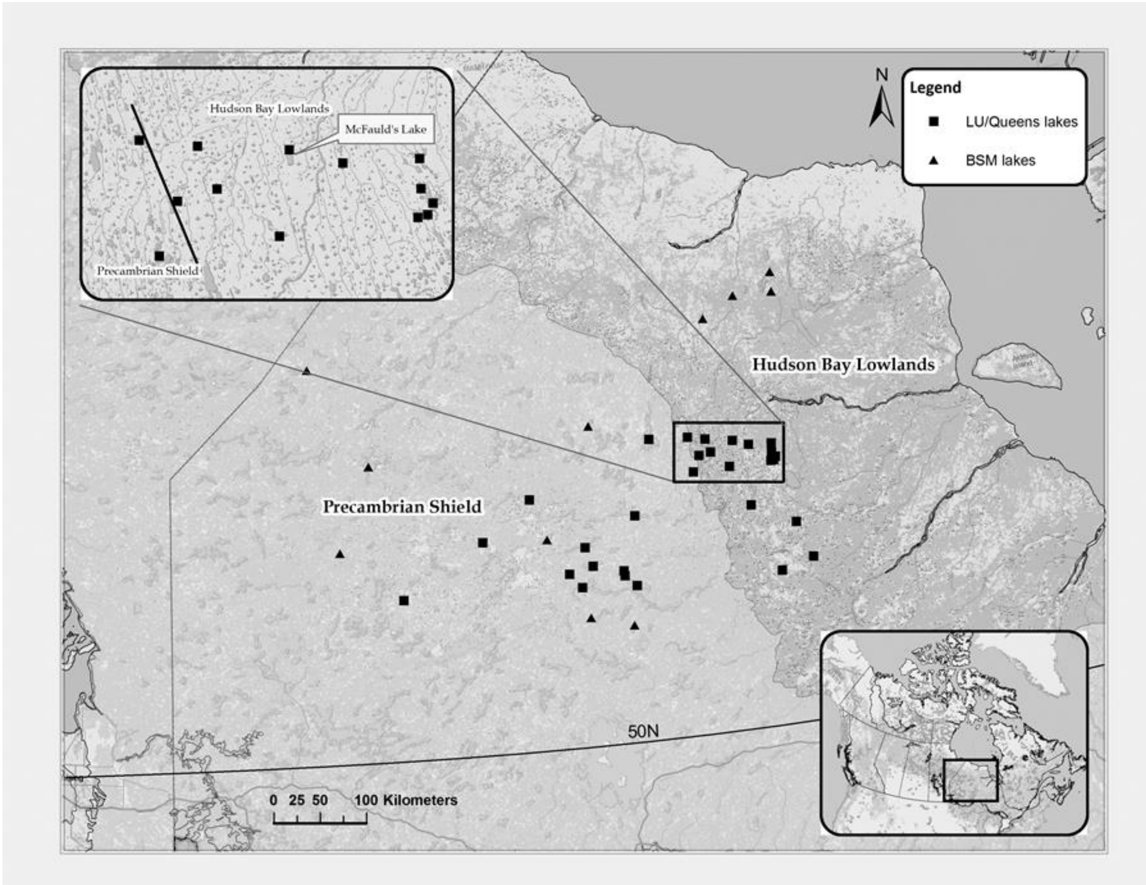

Figure 3-1: Lakes sampled in 2012 by Laurentian and Queen's Universities and the MNR's BSM survey.

3.3 Methods

The LU/Queen’s survey and the OMNR-BSM survey used the same sampling techniques. At a central location on each lake depth and transparency (Secchi depth) were determined using a sonar depth sounder and Secchi disk, respectively. An oxygen and temperature profile was recorded using a YSI model 52 oxygen meter with readings for every 1 m of water depth until within 1 m of the bottom.

A water sample was obtained at each lake using a composite depth sampling bottle. The device consisted of a large sealed bottle (~ 4 litre volume) with a metal handle and removable plastic cap. The cap has a 5 cm hole drilled into it allowing water to enter the sampler at a slow rate. The device was first rinsed with lake water before being secured to a rope and then lowered to the Secchi depth or 1 m off bottom (which ever was shallower) and then slowly retrieved allowing the bottle to fill with water evenly across all depths. Care was taken ensure that the bottle was not full before resurfacing. The water in the sampler was then filtered through an 80 µm mesh Nalgene funnel (funnel rinsed with surface water three times) to fill the final sample container (a large volume (6 L) jug). This process was repeated until the sample jug was full. Samples were stored in a cooler while in the field. At the end of each day the 6 L jugs of composite water samples were subsampled for each laboratory analysis, as appropriate. Sutey et al. (2011) describes the full set of bottles used for samples sent to the Dorset Environmental Laboratory of the Ontario Ministry of the Environment (MOE). Each of the sample bottles listed was rinsed three times with filtered water from the composite sampler before filling. These samples were carefully labelled and packed up in coolers with freeze-packs for transit back to Sudbury. There, they were kept overnight before being delivered to Dorset for analysis.

A zooplankton haul was done using a standard protocol for all lakes. Where depths exceeded 5 m, a vertical haul was performed from 1 m off bottom to the surface, while in shallower lakes a 4 m long horizontal haul was performed with the net completely submerged, but not contacting the bottom. Nets were non-metered and composed of 80µm polyester mesh (62 µm for the BSM survey) with a 30 cm diameter mouth. Samples from the LU/Queen's survey were preserved in the field with 15% formalin solution while the BSM survey used 85% ethanol as a field preservative. Because of the differential shrinkage caused by these different preservatives length-weight ratios could not be used to generate comparable biomass estimates. Therefore, only species counts were used.

3.3.1 Laboratory counting methods

Crustacean zooplankton were counted using the same methods as Paterson et al. (2014) Briefly, samples were split using a folsom plankton splitter. Individual species target counts of 45-60 for adults and 15-35 for juvenile copepods (calanoid or cyclopoid nauplii or copepodids) were obtained, with a minimum total count of 240 zooplankton to ensure that no one species comprised more than 20% of the total count. Data were expressed as relative abundance. Major keys used for identification were Brooks, 1957; Brooks, 1959; DeMelo and Hebert, 1994; Hebert, 1995; Smith and Fernando, 1978; Taylor et al., 2002; Wilson, 1959; and Yeatman, 1959.

3.3.2 Statistical Analysis

R v. 3.0.2 was used as the primary software for statistical analysis. Zooplankton abundance data for 2012 were first thinned by removing juvenile life stages and rare species (species which did not make up a minimum of 1% of the overall sample in at least 1 lake). The data were then converted to percentages. Twenty one species remained to be included in the ordination analysis (Appendix C). Biotic data were square root transformed to reduce the effects of very abundant taxa, but not standardized as they were all measured by the same scale.

Detrended Correspondence Analysis (DCA) was run using the Vegan add-on package for R (Figure 3-2). Axis lengths of DCA1 and DCA2 were 2.1 and 2.0 respectively which were < 3.0, indicating that linear ordination techniques (rather than unimodal) were suitable (Lepš and Šmilauer, 2003). Redundancy Analysis (RDA) was chosen for its ability to explore relationships between the species composition of lakes while including water chemistry variables as constraints to the ordination axes. The following chemistry variables were included in the RDA: lake depth, lake length, lake area, dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), Ca, Cl, Mg, K, Si, Na, SO_4, Fe, alkalinity, pH, true colour, total nitrogen (total N), inorganic nitrogen (IN), total phosphorus (TP) and conductivity. All were log^{10} transformed prior to analysis in order to achieve a near-normal distribution. A forward selection step was used with the RDA to reduce the number of co-linear constraining variables. Monte Carlo permutation tests (1000 permutations) were run to determine the significance of each forward selected variable, and to test the significance of each ordination axes defined by the forward selected constraining variables. Vectors of variables which were not included in the forward selection step were added into the plot figures post-analysis using permutational fitting to provide a visual reference of their relationship to the other data (i.e. they were included as passive samples).

A second analysis was run using the pooled data from the two previously mentioned surveys combined with data from Keller and Pitblado (1989) (n = 132 lakes, all Shield), Keller (2010 unpublished data, n = 6, all Lowlands) and Paterson et al. (2014, n = 17, all Lowlands). This is referred to as the composite analysis throughout this paper. Not all chemistry data were available across all data sets, therefore a subset of physical/chemical variables was used: lake depth, lake area, alkalinity, Ca, Cl, Mg, K, Na, SO_4, pH, total N (Kjeldahl), TP and conductivity. Latitude and longitude were also entered to search for spatial patterns since the combination of data sets covered a very large area. The same DCA and RDA approach was used as outlined above with gradient lengths of 3.2 and 2.7 for DCA 1 and 2 respectively.

When zooplankton data for the composite analysis were assembled, some species had to be combined to account for differences in taxonomy over the survey period (*D. catawba* and *D. pulicaria* were combined with *D. pulex* as *D. pulex* (complex), *Daphnia* sp. were divided among the other *Daphnia* species proportionally according to their abundance, *B. freyi* and *B. longirostris* were combined with *B. liederi* as *Bosmina* sp., *D. brachyurum* and *D. birgei* were combined as *D. birgei*, *E. lacustris* and *E. lacustris* copepodids were combined as *E. lacustris*, *E. speratus* was relabelled as *E. elegans*, *H. gibberum and H. glacialis were combined as H. glacialis*). The result was the species list found in Appendix D.

3.4 Results

Thirty four species of crustacean zooplankton were identified in the 41 lakes from the 2012 survey. The most common species were *Bosmina freyi, Chydorus sphaericus, Epischura lacustris, Daphnia mendotae, Holopedium glacialis, Diacyclops bicuspidatus thomasi, Diaphanosoma birgei, Leptodiaptomus minutus and Skistodiaptomus oregonensis* all of which occurred in more than 50% of the surveyed lakes. Species % occurrence is listed in Table 3-1.

Species richness in individual lakes ranged from 6 – 16 (Appendix E) and was significantly (positively) correlated (Spearman's correlation $p<0.01$) with lake depth ($r = 0.427$), lake area ($r = 0.356$), lake length ($r = 0.545$), longitude ($r = 0.502$), Ca ($r = 0.493$), DIC ($r = 0.480$), Mg ($r = 0.472$), reactive silicate ($r = 0.550$) and conductivity ($r = 0.489$).

Table 3-1: Relative occurrence of crustacean zooplankton species in 2012 survey lakes (n=41, 22 Shield, 19 Lowlands).

Species	Abbreviation	% of all lakes	% of Shield lakes	% of Lowlands lakes
Bosmina freyi	B. frey	100.0	100.0	100.0
Chydorus sphaericus	Ch sphaer	92.7	86.4	100.0
Epischura lacustris	Ep lac cp	85.4	77.3	94.7
Daphnia mendotae	Da. m	78.0	90.9	63.2
Holopedium glacialis	Hol glac	78.0	86.4	68.4
Diacyclops bicuspidatus thomasi	Cy bi thom	78.0	90.9	63.2
Diaphanosoma birgei	Dia birg	73.2	81.8	63.2
Leptodiaptomus minutus	Lepto minu	61.0	45.5	78.9
Skistodiaptomus oregonensis	Skis oreg	56.1	77.3	31.6
Ceriodaphnia sp.	Cerio sp	36.6	45.5	26.3
Tropocyclops extensus	Trop ext	36.6	50.0	21.1
Daphnia longiremis	Da. long	31.7	59.1	0.0
Daphnia retrocurva	Da. retr	22.0	31.8	10.5
Leptodora kindtii	Lep. kind	22.0	22.7	21.1
Alona sp.	Alona sp	19.5	18.2	21.1
Acanthocyclops vernalis complex	Cyc vern c	19.5	22.7	15.8
Mesocyclops edax	Meso edax	19.5	36.4	0.0
Sida crystallina	Sida crys	14.6	13.6	15.8
Eubosmina longispina	E. long	14.6	18.2	10.5
Daphnia catawba	Da. cat	12.2	9.1	15.8
Bosmina liederi	B. lied	9.8	9.1	10.5
Eubosmina sp.	Eub sp	9.8	18.2	0.0
Polyphemus pediculus	Pol pedic	7.3	9.1	5.3
Harpacticoida sp.	Harp sp	7.3	9.1	15.8
Acroperus harpae	Ac harp	4.9	4.5	5.3
Daphnia pulicaria	Da. pul	4.9	4.5	5.3
Leptodiaptomus siciloides	Lep sicilo	4.9	9.1	0.0
Eucyclops agilis	Eucy agil	4.9	4.5	5.3
Eurycercus lamellatus	Eury lam	2.4	0.0	5.3
Latona setifera	Lat. setif	2.4	4.5	0.0
Daphnia sp.	Dap sp	2.4	4.5	0.0
Graptoleberis testudinaria	Grap tes	2.4	0.0	5.3
Leptodiaptomus ashlandi	Lepto ashl	2.4	4.5	0.0
Leptodiaptomus sicilis	Lepto sicil	2.4	4.5	0.0
Macrocyclops albidus	Mac albid	2.4	0.0	5.3

DCA determined axis lengths of 2.1 and 2.0, which necessitated further analysis with a linear technique, in this case an RDA. Ordination output from the DCA is provided for comparison (Figure 3-2). RDA ordination characterized general trends and identified the primary sources of environmental and biological variation among the 41 lakes (% of variation explained: RDA1 = 8.4%, RDA2 = 5.8%, RDA3 = 4.7%, Appendices F and G). The species with the strongest positive loadings on RDA1 were *D.b. thomasi* (0.663) and *D. longiremis* (0.516). The species with the strongest negative loadings on RDA1 were *T. extensus* (-0.495), *C. sphaericus* (-0.433) and *E. lacustris* (-0.660). The only species with a strong positive loading on RDA2 was *C. sphaericus* (0.689). The only species with strong negative loadings on RDA2 was *Ceriodaphnia* sp. (-0.523). The only species with a strong positive loading on RDA3 was *Alona* sp. (0.496). The only species with strong negative loadings on RDA3 was *D. longiremis* (-0.544).

Figures 3-3 to 3-4 show the first two axes from the forward selection RDA. Chemistry variables not forward selected by the analysis were fit onto the graph afterwards by permutation for comparative purposes. Lakes in the top left quadrant were mostly Lowlands lakes from the ROF area. They were characterized by higher nutrients (DOC, TN, TP) and true colour, smaller lake size, lower ionic strength, and smaller lake length, depth and area. *C. sphaericus* had the highest relative abundance among species in these lakes (Figure 3-4). Lakes in the bottom right quadrant were Shield lakes from the center of the study area, near Fort Hope (Figure 3-3). They were associated with high ion concentrations (Ca, Mg, K, Si, SO_4), conductivity, alkalinity, pH and greater lake area/depth. *D. longiremis, D. retrocurva* and *M. edax* had the highest relative abundance among species in these lakes (Figure 3-4). Lakes in the top right quadrant were scattered, but included most lakes closest to Hudson Bay (Figure 3-3). They were characterized by comparatively high Cl ion concentrations. *E. longispina* and *L. ashlandi, D. mendotae, D.b. thomasi* and *L. sicilis* had the highest relative abundance among species in these lakes (Figure 3-3). The bottom left quadrant lakes were also scattered geographically. They had higher Fe and inorganic N, with lower Cl ion concentrations. *T. extensus, B. freyi,* and *Ceriodaphnia* sp. were the species most abundant in lakes from this quadrant (Figure 3-4).

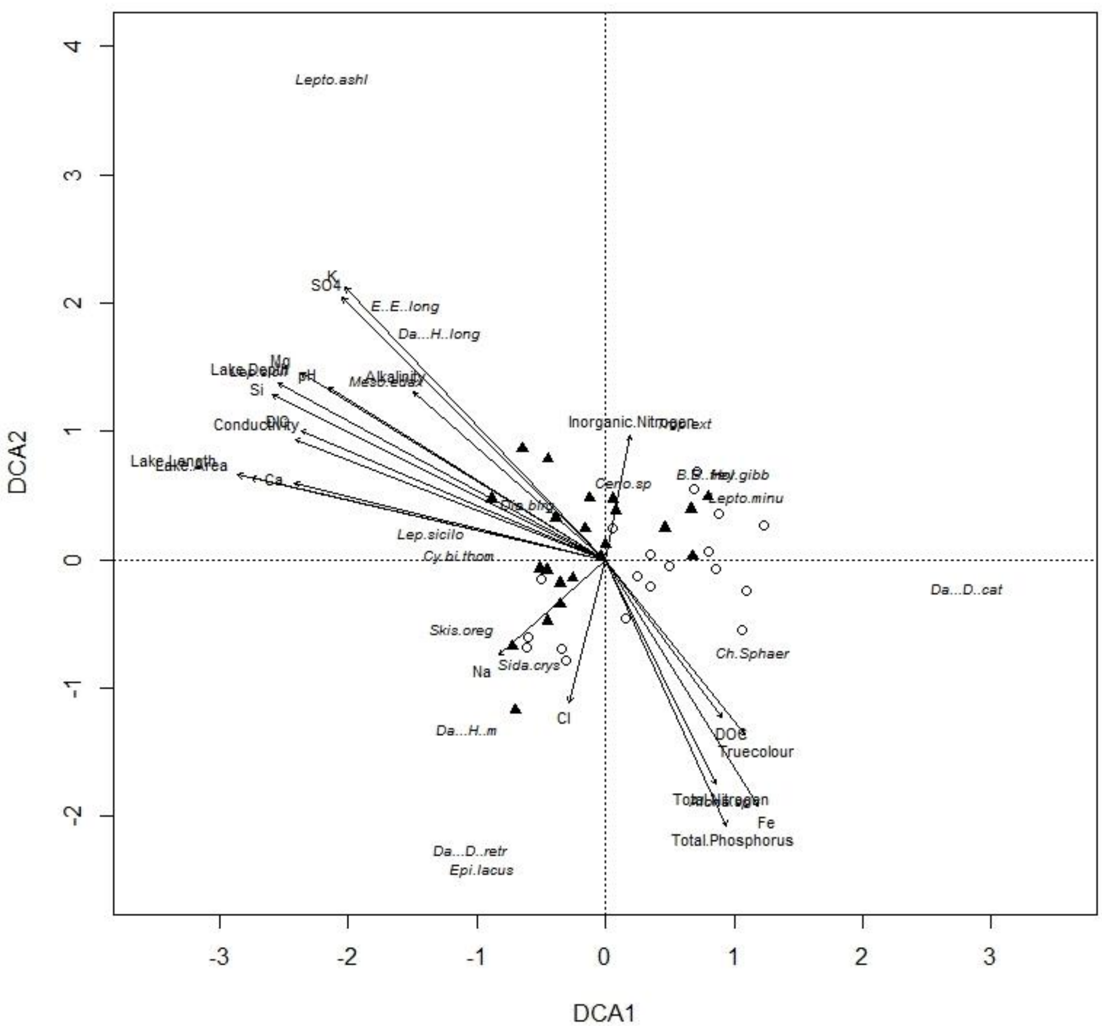

Figure 3-2: DCA ordination plot of 2012 survey lakes (n=41; 22 Shield, 19 Lowlands), lakes labeled by region: Shield (triangles) and Lowlands (circles). Species in italics.

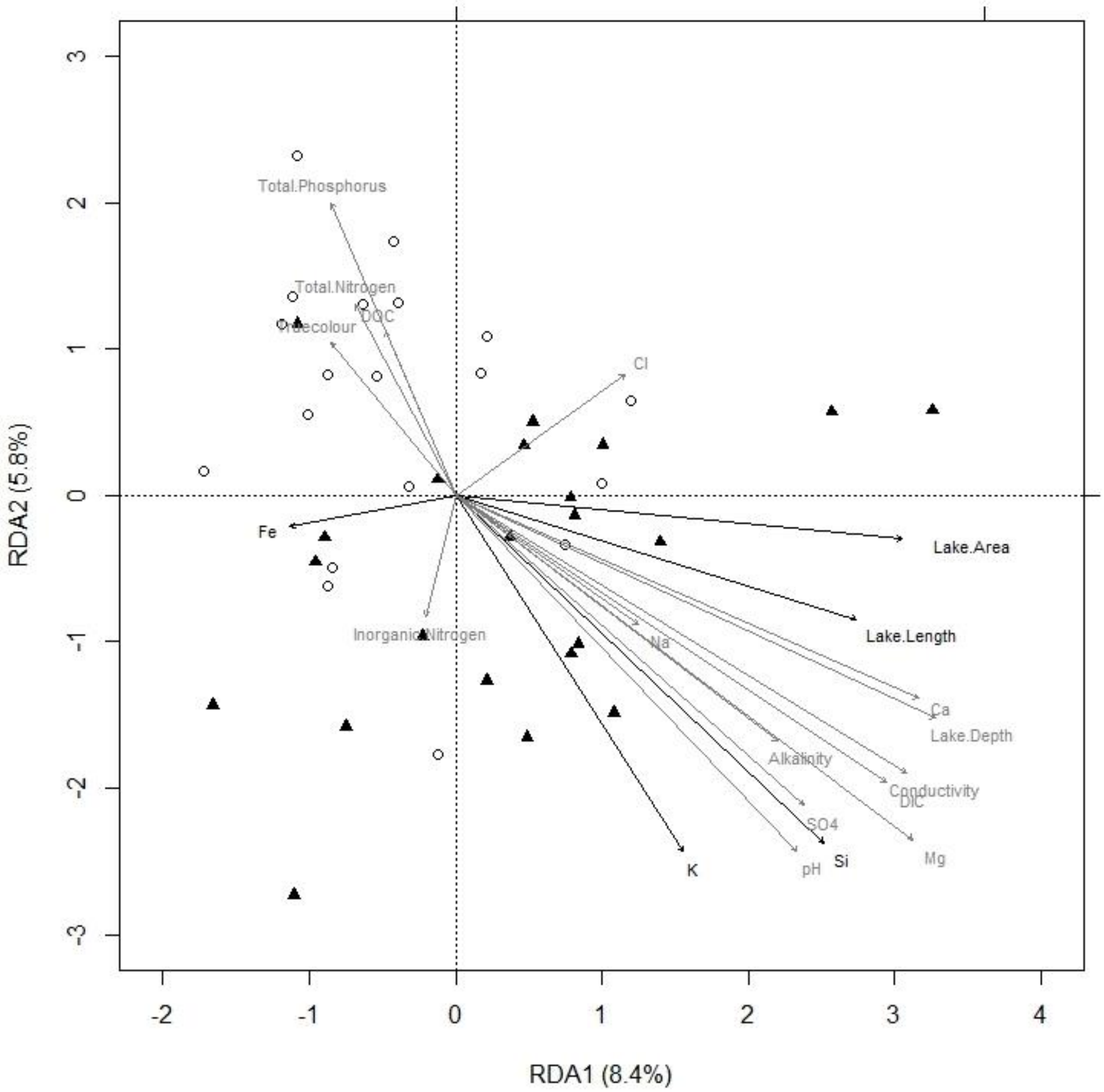

Figure 3-3: RDA ordination plot of 2012 survey lakes: chemistry variables in regular font, lakes labeled by region: Shield (triangles) and Lowlands (circles) (n=41; 22 Shield, 19 Lowlands). Passive chemistry variables (not run in analysis) shown in grey.

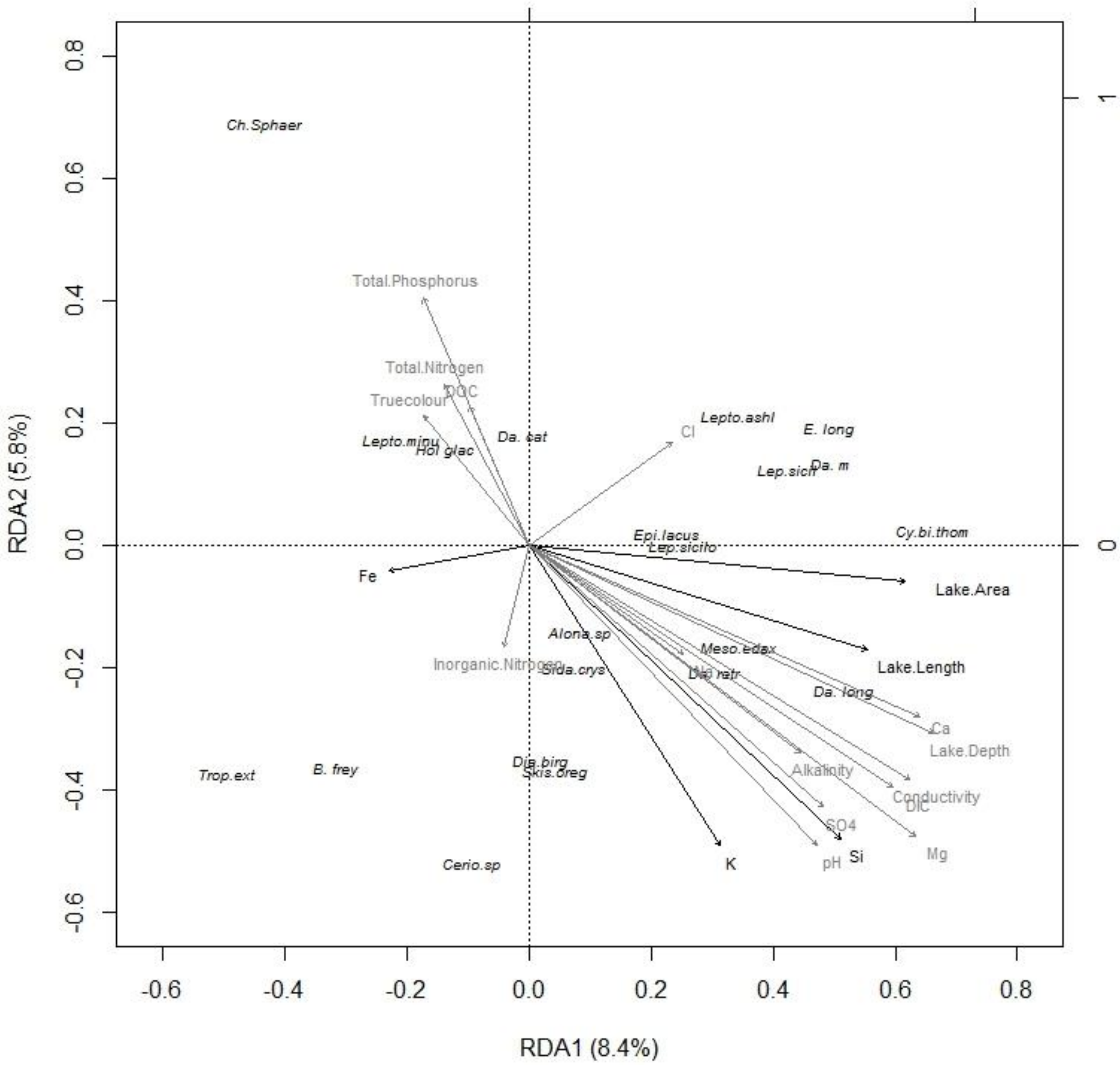

Figure 3-4: RDA ordination plot of 2012 survey lakes (n=41 lakes): Species in italics, chemical variables in regular font, passive chemical variables shown in grey.

For the composite year analysis, which combined the LU/Queens/BSM 2012 data with data from 1981 (Keller and Pitblado, 1989) and 2009-2011 (Paterson et al., 2014; and Keller, 2010 unpublished data), DCA determined axis lengths of 3.3 and 2.7, which necessitated further analysis with a linear technique, in this case an RDA. Ordination output from the DCA is provided for comparison (Figure 3-5). RDA analysis identified the primary sources of variability among the 196 lakes (% of variation explained: RDA1 = 5.6%, RDA2 = 3.2%, RDA3 = 2.2%, Appendicies H and I). The species with the strongest positive loadings on RDA1 were *Eubosmina* sp. (0.680) and *Bosmina* sp. (0.651) while the species with the strongest negative loadings on RDA1 were *M. edax* (-0.825), *D. retrocurva* (-0.737), *D. mendotae* (-0.677) and *H. glacialis* (-0.586). The species with the strongest positive loadings on RDA2 were) *Ceriodaphnia* sp. (0.619) and *C. sphaericus* (0.537), while the only species with strong negative loadings on RDA2 was *L. minutus* (-0.757). The only species with strong positive loadings on RDA3 was *S. oregonensis* (0.322) while the species with the strongest negative loadings on RDA3 were *L. sicilis* (-0.636), *D. b. thomasi* (-0.469) and *D. mendotae* (-0.449) (Figures 3-6 and 3-7).

Lakes in the top right quadrant of Figure 3-6 included the majority of the 2012 survey lakes. They were associated with high total N and larger lake areas. *Ceriodaphnia* sp., *C. sphaericus*, *E. longispina*, and *Alona* sp. were most abundant in these lakes (Figure 3-8). Nearly all the lakes from the northeastern group (Paterson et al., 2014; Keller, 2010 unpublished data) were located in the bottom right quadrant. These lakes were associated with higher Cl and Na ions and have higher abundances of *Eubosmina* sp., *L. minutus*, *D.b. thomasi*, *and D. pulex* (complex) (Figure 3-8). Lakes towards the lower left were mostly from Keller and Pitblado (1989), which covers the area south of 50°N and west of

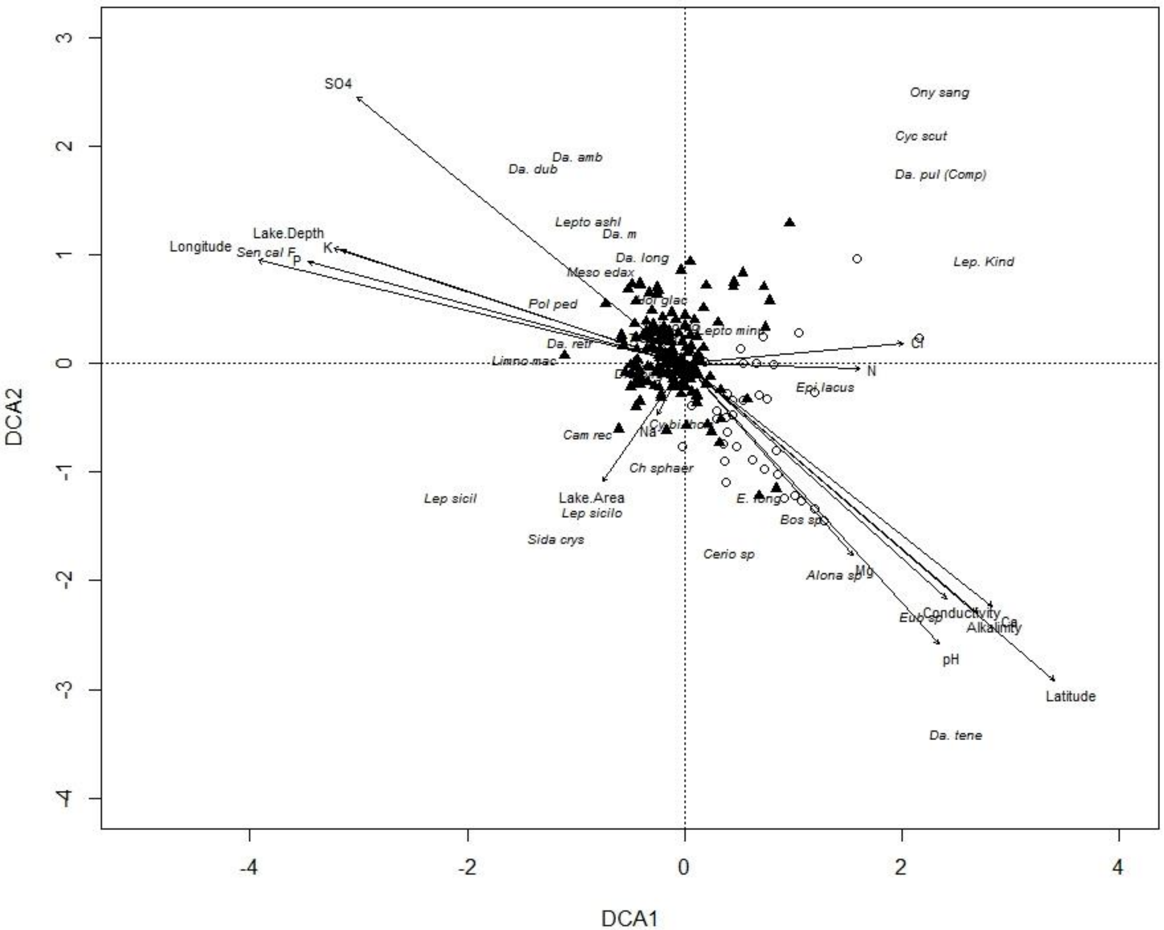

Figure 3-5: DCA ordination plot of combined analysis data (n=196). Lakes labelled by region: black triangles = Shield, open circles = Lowlands. Species in italics. Passive chemistry variable vectors were permutationally fit onto the plot post-analysis.

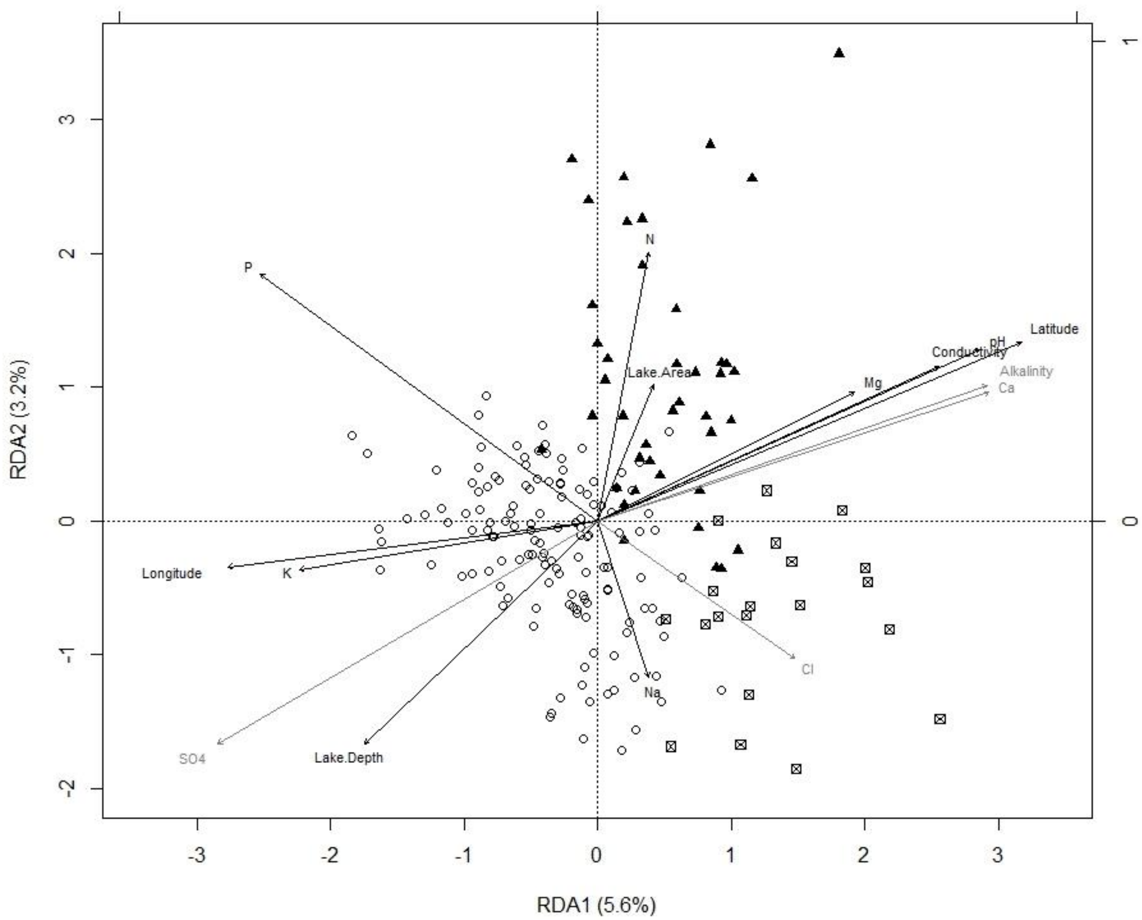

Figure 3-6: RDA ordination of combined analysis: Chemistry variables in regular font, species in italics. Lakes labelled by survey: open circles = Keller and Pitblado (1989), solid squares = Paterson et al. (2014) and Keller, 2010 unpublished data, solid triangles = LU/Queen's (2012) (n=196 lakes).

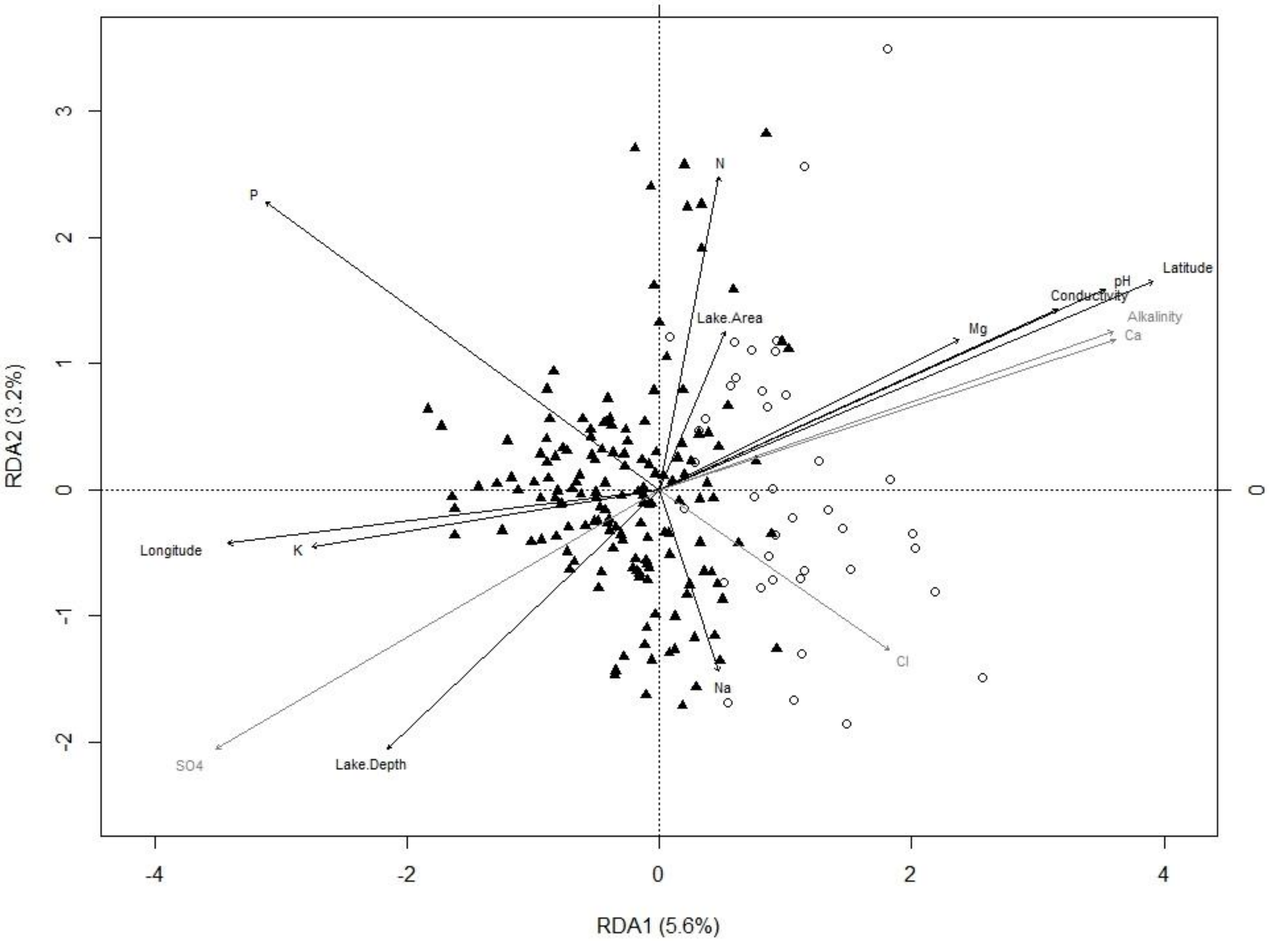

Figure 3-7: RDA ordination of combined analysis: Chemistry variables in regular font, species in italics. Lakes labelled by region: black triangles = Shield, open circles = Lowlands (n=196 lakes).

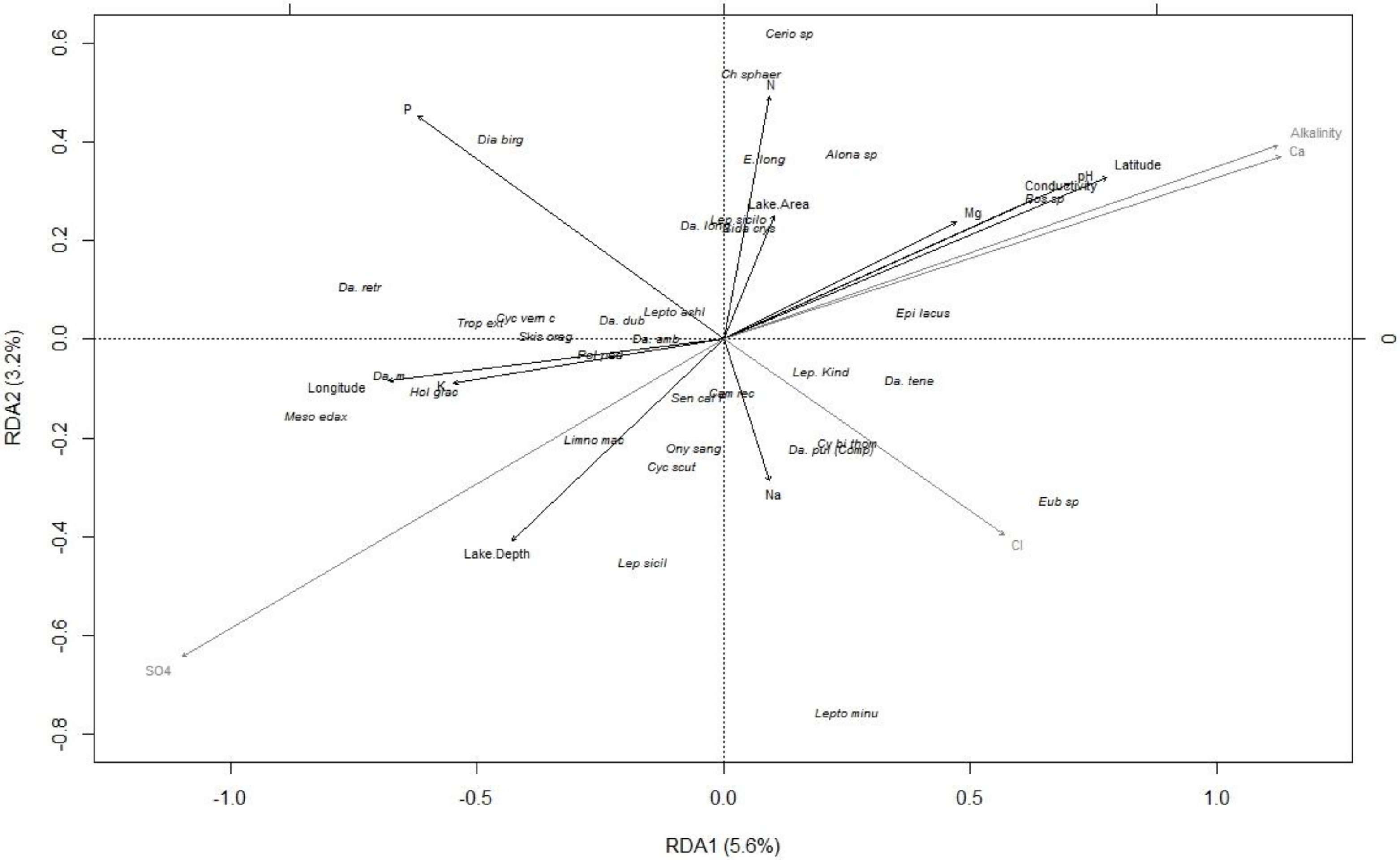

Figure 3-8: RDA ordination of combined analysis: Chemistry variables in regular font, species in italics. Lakes are not identified (n=196 lakes).

Thunder Bay. These lakes were deeper with higher SO_4 and K ions and had higher relative abundances of *M. edax, H. glacialis, D. mendotae,* and *L. sicilis,* (Figure 3-8). The Lowlands lakes were generally oriented further to the right of the ordination, indicating higher pH, Ca, Mg and conductivity, shallower lake depth and lower P (Figure 3-7).

Excluding those variables which were not available for both analyses (lake length, latitude, longitude, DIC, DOC, Si, Fe, true colour and inorganic N), the variables which loaded highly on RDA 1-3 from the combined analysis and did not load highly on RDA 1-3 from the 2012 analysis were P, total N, Mg, pH, lake depth, Na and conductivity. Conversely, lake length was the only variable which loaded highly on the first three RDA's from the 2012 analysis but did not load highly on the first three RDA's from the combined analysis. With regards to species loadings, *C. sphaericus, D. mendotae, B. freyi, L. minutus, S. oregonensis, D.b. thomasi, T. extensus, Ceriodaphnia* sp.*, L. sicilis, Alona* sp. and *E. longiremis* all had high loadings within RDA 1-3 of both surveys (Appendices H and I).

3.5 Discussion

The 2012 study lakes supported a diverse assemblage of crustacean zooplankton species similar to other lakes in Ontario. Species richness in this survey (6-16 species per lake, 34 total species) was similar to that of Keller and Conlon (1994) (5-15 species per lake, 28 total) and Keller and Pitblado (1989) (NW lakes 6-17 species per lake, 37 total) for Shield lakes and Paterson et al. (2014) (6-12 species per lake, 30 total) for Lowlands lakes. Of

Table 3-2: Comparison of species occurrence in lakes of the 2012 survey to occurrence of these species in other northern Ontario zooplankton studies.

Species	% of 2012 lakes (n=41)	% of N lakes from Paterson et al. (2014) and Keller, W. (unpublished data) (n=20)	% of NW lakes from Keller and Pitblado (1989) (n=137)	% of NE lakes from Keller and Pitblado (1989) (n=161)	% of N lakes from Keller and Pitblado (1989) (n=39)	% of Algoma lakes from Keller and Conlon (1994) (n=60)
***Bosmina* sp.**	100.0	100.0	96.3	95.0	92.0	92.0
Chydorus sphaericus	92.7	80.0	79.3	27.0	82.0	7.0
Epischura lacustris	85.4	80.0	51.9	64.0	72.0	42.0
Daphnia mendotae	78.0	60.0	92.6	80.0	80.0	40.0
Holopedium glacialis	78.0	45.0	77.0	90.0	49.0	68.0
Diacyclops bicuspidatus	78.0	80.0	95.6	89.0	95.0	27.0
Diaphanosoma birgei	73.2	20.0	79.3	85.0	51.0	50.0
Leptodiaptomus minutus	61.0	85.0	94.8	94.0	41.0	92.0
Skistodiptomus oregonensis	56.1	55.0	63.0	71.0	74.0	42.0
***Ceriodaphnia* sp.**	36.6	5.0	20.0	21.0	26.0	3.0
Tropocyclops extensus	36.6	10.0	74.8	71.0	5.0	88.0
Daphnia longiremis	31.7	20.0	24.4	67.0	39.0	17.0
Daphnia retrocurva	22.0	0.0	61.5	66.0	72.0	15.0
Leptodora kindtii	22.0	10.0	7.4	24.0	46.0	8.0
***Alona* sp.**	19.5	15.0	3.0	0.0	0.0	0.0
***Acanthocyclops vernalis* complex**	19.5	10.0	38.5	18.0	56.0	0.0
Mesocyclops edax	19.5	10.0	73.3	87.0	46.0	88.0
***Daphnia pulex* group**	14.6	35.0	11.9	26.0	5.0	52.0
Sida crystallina	14.6	10.0	2.2	9.0	18.0	3.0
Eubosmina longispina	14.6	5.0	0.0	32.0	0.0	17.0
***Eubosmina* sp.**	9.8	35.0	0.0	0.0	0.0	0.0
Polyphemus pediculus	7.3	15.0	8.1	0.0	0.0	8.0
Harpacticoida nauplii	7.3	5.0	0.0	0.0	0.0	0.0
***Harpacticoida* sp.**	7.3	0.0	0.0	0.0	0.0	0.0
Acroperus harpae	4.9	0.0	0.0	0.0	0.0	0.0
Leptodiaptomus siciloides	4.9	0.0	0.0	0.0	0.0	0.0
Eucyclops agilis	4.9	10.0	0.7	0.0	0.0	0.0
Eurycercus lamellatus	2.4	5.0	0.0	0.0	0.0	0.0
Latona setifera	2.4	5.0	0.0	0.0	0.0	0.0
Graptoleberis testudinaria	2.4	0.0	0.0	0.0	0.0	0.0
Leptodiaptomus ashlandi	2.4	0.0	1.5	3.0	46.0	0.0
Leptodiaptomus sicilis	2.4	0.0	30.4	15.0	18.0	3.0
Macrocyclops albidus	2.4	0.0	0.0	0.0	0.0	0.0
Daphnia tenebrosa	0.0	10.0	0.0	0.0	*26.0	0.0
Acantholeberis curvirostris	0.0	5.0	0.0	0.0	0.0	0.0
Limnocalanus macrurus	0.0	0.0	14.1	3.0	8.0	0.0
Cyclops scutifer	0.0	0.0	8.1	65.0	15.0	5.0
Onychodiaptomus	0.0	0.0	4.4	0.0	0.0	5.0
Daphnia dubia	0.0	0.0	3.7	22.0	0.0	30.0
Daphnia ambigua	0.0	0.0	1.5	21.0	0.0	0.0
Senecella calanoides	0.0	0.0	1.5	0.0	0.0	7.0
Orthocyclops modestus	0.0	0.0	1.5	0.0	0.0	15.0
Eubosmina coregoni	0.0	0.0	0.7	0.0	0.0	8.0
Eucyclops elegans	0.0	0.0	0.7	0.0	0.0	0.0
Camptocercus rectirostris	0.0	0.0	0.7	0.0	0.0	0.0
Eubosmina tubicen	0.0	0.0	0.0	27.0	0.0	0.0
Aglaodiaptomus leptopus	0.0	0.0	0.0	0.0	0.0	27.0

*reported as *D. middendorfiana*

the 34 species identified, 28 of them occurred in lakes from past Ontario surveys. Table 3-2 shows the % occurrence of all species for each of the above mentioned surveys.

Positive correlations of species richness with morphometry (lake area, lake depth, lake length) indicated that larger, deeper lakes support a more diverse array of zooplankton, which is consistent with the theory of island biogeography (MacArthur and Wilson, 1967). Deeper, larger lakes provide a more variable habitat, which increases the available niche space, leading to more biodiversity. A direct example of this is the distribution of hypolimnetic species such as *D. longiremis,* which are not likely to successfully colonize shallower waters (Keller, 1993) and were only found in the deeper Shield lakes in this survey (Table 3-1). Ca, Mg and conductivity were all correlated with richness, because these three variables were all higher in the deeper Shield lakes, which had higher zooplankton richness than the Lowlands lakes. Ca levels in all lakes were well above 2.5 mg/L, so it is unlikely to have negatively affected distributions of Ca sensitive *Daphnia* species (Tessier and Horwitz, 1990; Jeziorski et al., 2008).

Species present in over 50% of the 2012 lakes (*B. freyi, C. sphaericus, E. lacustris, D. mendotae, H. glacialis, D. bicuspidatus thomasi, D. birgei, L. minutus and S. oregonensis*) were also common in other surveys of Ontario lakes that generally have been conducted in more southern areas of the province, on the Precambrian Shield (Table 3-2). Thus, lakes from this survey were similar in zooplankton community richness and species composition to lakes elsewhere in Ontario.

Many of the species common in the 2012 study lakes, including *Bosmina* sp., *C. sphaericus*, *H. glacialis*, *D. b. thomasi*, *L. minutus*, *E. lacustris*, and *A. vernalis* have also been commonly reported from arctic and subarctic lakes (Hebert and Hann, 1986; Swadling et al., 2001; Symons et al., 2014). However, species characteristic of Arctic/Subarctic lakes futher north, such as *D. tyrrelli*, and *D. middendorfiana/tenebrosa* (Hebert and Hann, 1986; Swadling et al., 2001; Symons et al., 2014) were not found in the 2012 survey lakes indicating that these lakes are all south of the distribution of these species.

Despite the fact that they are located in different Ecozones, Lowlands (Hudson Plains Ecozone) and Shield (Boreal Shield Ecozone) lakes in the 2012 survey had generally similar species composition. Of the species which had > 20% differences in occurrence between Shield and Lowlands lakes, most were still reasonably common in both sets of lakes (> 20 % occurrence in each lake set, Table 3-2). Exceptions were *D. longiremis* and *M. edax* which were absent from the Lowlands lakes collections. As indicated earlier, the absence of *D. longiremis*, a hypolimnetic species, from the shallow Lowlands lakes is not surprising given the thermal habitat limitations in these shallow lakes. The reason for the absence of *M. edax* from the Lowlands lakes is not clear; however, in agreement with results from this survey, the species does seem to be generally restricted to more southerly lakes. *M. edax* was very rare in subarctic lakes further north in Ontario (Paterson et al., 2014) and was not reported from surveys of subarctic and arctic lakes further north in Canada (Hebert and Hann, 1986; Swadling et al., 2001; Symons et al., 2014). It appears that this survey may have been conducted near the northern limit of the range of *M. edax*. This may also be the case for *T. extensus* and possibly *D. mendotae*, which were common in this survey but rare or absent from surveys further north (Hebert and Hann, 1986; Swadling et al., 2001; Paterson et al., 2014; Symons et al., 2014). The absence of *C. scutifer* from the 2012 survey lakes agrees with previous observations of scarcity in northwestern Ontario (Keller and Pitblado, 1989).

While Shield and Lowlands lakes did support generally similar zooplankton assemblages, in analyses at both spatial scales, Shield and Lowlands lakes did separate on the RDA ordinations (Figures 3-3 and 3-7). Considering loadings on the first three axes, while some species loaded strongly on both the 2012 and combined ordinations (*C. sphaericus, D. mendotae, B. freyi, L. minutus, S. oregonensis, D.b. thomasi, T. extensus, Ceriodaphnia* sp.*, L. sicilis, Alona* sp. and *E. longiremis*) a number of species loaded strongly on only one ordination, with more species characterizing the axes of the combined ordination (*D. pulex, H. glacialis, D. birgei, M. edax* and *D. retrocurva*) than the 2012 ordination (*D. longiremis*). Since the combined lake set encompassed a much greater number of lakes along a much wider gradient of physico-chemical variability it is logical that more species/environment relationships would be detected in the analysis of patterns in those lakes.

However, while some species with high loadings in the RDA's differed between the 2012 (Appendix F) and combined analyses (Appendix H), most of these species were relatively common in both datasets (Table 3-2). This suggests that changes in the abundance of common species as well as changes in species occurrence were important to the outcome of the analyses. The fact that most of the observed interspecies correlations were positive suggests that most species were responding to environmental gradients in a similar fashion. There were comparatively few instances of negative species correlations that might indicate competitive or predatory interactions. A particular exception was the very common species *Bosmina* sp., which had a significant ($p < 0.01$) negative correlation with *D. mendotae* suggesting a competitive interaction (DeMott and Kerfoot, 1982). *Bosmina* sp. was also negatively correlated with *D.b. thomasi* suggesting a possible predator/prey interaction.

The defining physico-chemical characteristics of the Shield lakes compared with the Lowlands lakes were greater ionic strength (Ca, Mg and conductivity), pH, alkalinity, lake area and lake depth. Because of its influence on habitat diversity and niche space morphometry is likely the strongest driver of differences in communities between these lakes. Lake length and lake area were the two strongest predictors of zooplankton community composition. Other strong correlates were ionic strength (Ca, K, and SO_4), reactive silicate, TP, total N, Fe and Na (Figure 3-3). This finding is consistent with prior surveys of Ontario lakes that have identified lake morphometry as a major correlate with zooplankton community composition (Keller and Pitblado, 1981; Keller and Conlon, 1994), and have demonstrated strong links between depth, nutrient status, and zooplankton community structure (Keller and Conlon, 1994; Keller et al., 2002; Yan et al., 2008).

Although clear relationships between crustacean zooplankton communities and lake physico-chemical characteristics have emerged from this analysis, much of the variation in community structure remained unexplained. This probably largely reflects the fact that this analysis did not include evaluation of the possible effects of biological controls on species assemblages, which can be very important (Keller et al., 1992; Keller and Yan, 1998). Planktivorous fish (Valois et al., 2010; Webster et al., 2013) and in their absence macroinvertebrate predators (Yan et al., 1991; MacPhee et al., 2011) can have strong effects on zooplankton prey communities. Biological controls on zooplankton assemblages may be particularly intense in very shallow lakes, such as most of the lakes in the Hudson Bay Lowlands, which may offer little habitat separation between species (Keller and Conlon, 1994). An important future research direction would be the evaluation of the roles of vertebrate and invertebrate predators in structuring northern zooplankton communities.

3.6 Conclusions

The 2012 study lakes in northwestern Ontario supported relatively diverse crustacean plankton communities with species richness similar to the species richness of lakes previously surveyed in other parts of Ontario. The species most common in these lakes were also commonly found in other Ontario surveys. While some of the species collected including *M. edax*, *T. extensus*, and *D. mendotae*, appear to be at the northern limit of their Ontario distributions, most relatively common Ontario species occurred throughout the 2012 study area.

The major physico-chemical correlates with species relative abundance and richness were variables associated with lake morphometry (lake depth, lake area and lake length), followed by nutrients and ionic strength. This suggests that while there were differences in community richness and composition between Lowlands and Shield lakes these differences do not seem attributable to biogeographic influences on species distributions.

Rather, the lower species richness and different community composition in Lowlands lakes relative to Shield lakes appears to be primarily related to lake morphometry. The shallow Lowlands lakes provide much less habitat diversity, i.e. niche space, than the deeper Shield lakes leading to simpler communities.

4 General Conclusions

The primary focus of this thesis was to assess possible differences in the chemistry and biotic communities of Precambrian Shield lakes and Hudson Bay Lowlands lakes in the Far North of Ontario. Shield lakes were deeper, with generally higher ionic strength, lower nutrients and higher zooplankton species richness than the Lowlands lakes. The glacial activity which carved these deep lakes and provided the habitat for hypolimnetic zooplankton species also provided the glacial till which gives Shield lakes in the northwest of Ontario their relatively high Ca and Mg concentrations (relative to Shield lakes south of 50°N): The finding that Shield lakes of northwestern Ontario north of 50°N had higher ionic strength (Ca, Mg) than previously reported for most Shield lakes is an important contribution to our understanding of lake chemistry in this relatively unstudied region.

Zooplankton communities in lakes in the northwest of Ontario were generally similar in composition and richness to those found elsewhere in the northern parts of the province. In agreement with previous Ontario surveys, lake morphometry was found to be a strong predictor of community composition across this region.

Lakes in the ROF region have highly diverse water chemistry, the product of a complex landscape with rather unpredictable patterns that probably reflect varying combinations of bogs, fens, glacial till and permafrost. This study illustrated that Shield Lakes in the ROF area are more similar to lakes in the vast peatlands of the Lowlands than typical Shield lakes in more southern regions.

This assessment of lake chemistry and zooplankton species assemblages within and surrounding the ROF region has provided several valuable insights into the existing conditions of lakes in this region. Providing baseline data on water chemistry and zooplankton community composition on these two different spatial scales is an invaluable tool for designing future environmental monitoring programs. It is hoped that such information will help managers conserve this region in the face of climate change and impending industrial development.

5 References

Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G.A., and Winder, M. 2009. Lakes as sentinels of climate change. Limnol. Oceanogr. 54: 2283–2297.

Anderson, M.J. 2001. A new method for non-parametric multivariate analysis of variance. Aust. Ecol. 26: 32–46.

Anisimov, O.A., and Nelson, F.E. 1996. Permafrost distribution in the northern hemisphere under scenarios of climatic change. Glob. Planet. Change 14: 59–72.

Armstrong, F.A.J., and Schindler, D.W. 1971. Preliminary chemical characterization of waters in the experimental lakes area, northwestern Ontario. J. Fish. Res. Board Canada 28: 171–187.

Barnett, P.J., Yeung, K.H., and McCallum, J.D. 2013. Surficial geology of the Lansdowne House area northeast, northern Ontario; Ontario Geological Survey, Preliminary Map P.3697, scale 1:100 000

Bos, D.G., and Pellatt, M.G. 2012. The water chemistry of shallow ponds around Wapusk national park of Canada, Hudson Bay Lowlands. Can. Water Resour. J. 37: 163–175.

Brooks, J.L. 1957. The systematics of North American *Daphnia*. Mem. Conn. Acad. Arts & Sciences 13: 1-180

Brooks, J.L.1959. Cladocera. pp. 587-656 in Edmondson, W.T. (ed). Freshwater Biology. 2nd ed. John Wiley and Sons, Inc., New York.

Brown, J., Ferrians, O.J.J., Heginbottom, J.A., and Melnikov., E.S. 2002. Circum-arctic map of permafrost and ground-ice conditions. Version 2. [Geographic North Pole - Permafrost Classification]. National Snow and Ice Data Center., Boulder, Colorado USA.

Chapman, M.G., and Underwood, A.J. 1999. Ecological patterns in multivariate assemblages: information and interpretation of negative values in ANOSIM tests. Mar. Ecol. Progess Ser. 180: 257–265.

Clarke, K.R. 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18: 117–143.

Colombo, S.J., McKenney, D.W., Lawrence, K.M., and Gray, P.A. 2007. Climate change projections for Ontario: practical information for policymakers and planners. Applied Research and Deveolpment Branch - Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario.

DeMott, W. R. and Kerfoot W. C. 1982. Competition among Cladocerans: Nature of interaction between Bosmina and Daphnia. Ecology 63:1949-1966

Devito, K.J., Hill, A.R., and Roulet, N. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. J. Hydrol. 181: 127–147.

Dyer, R.D. 2011. Project Unit 11-024. McFaulds Lake area lake sediment and water pilot study, northern Ontario. Sudbury, Ontario.

Dyer, R.D., and Handley, L.A. 2013. McFaulds Lake (“Ring of Fire”) area high density lake sediment and water survey, Far North, Ontario.

Everitt, B. 1974. Cluster Analysis. Edited by J. Mitchell. Heinemann Educational Books, London.

Four Rivers Matawa Environmental Services Group 2013. Surficial geology and infrastructure (1:700 000 scale map). NAD1983 UTM Zone 16N, Ontario Ministry of Natural Resources, Ontario Ministry of Northern Development and Mines.

Gagnon, A.S., and Gough, W.A. 2005. Climate change scenarios for the Hudson Bay region: An intermodel comparison. Clim. Chang. 69: 269–297.

Gough, W., Cornwell, A. and Tsuji, L. 2004. Trends in seasonal sea ice duration in southwestern Hudson Bay. Arctic 57:299-305

Hassan, R., Scholes, R., and Ash, N. (Editors). 2005. Ecosystems and human well-being: current state and trends, Vol. 1 of the Millennium Ecosystem Assessment Report. Island Press, Washington.

Hebert, P.D.N. 1995. The *Daphnia* of North America – An illustrated fauna. CD-ROM and website (http://www.cladocera.uoguelph.ca/taxonomy/daphnia/default.htm). University of Guelph.

Hebert, P.D.N., and Hann, B.J. 1986. Patterns in the composition of arctic tundra pond microcustacean communities. Can. J. Fish. Aquat. Sci. 43:1416-1425

Heginbottom, J.A., Dubreuil, M.A., and Harker, P.A. 1995. Canada permafrost. Geomatics Canada. National Atlas Information Service and Geological Survey of Canada, Ottawa.

Heinselman, M.L. 1963. Forest sites, bog processes, and peatland types in the glacial Lake Agassiz region, Minnesota. Ecol. Monogr. 33: 327–374.

Hessen, D.O., Faafeng, B.A., Smith, V.H., Bakkestuen, V., and Walseng, B. 2006. Extrinsic and intrinsic controls of zooplankton diversity in lakes. Ecology 87: 433–443.

Hochheim, K.P., and Barber, D.G., 2014. An update on the ice climatology of the Hudson Bay system. Arctic, Antarctic, and Alpine Research 46:66-83

Hochheim, K.P., Lukovich, J.V., and Barber, D.G., 2011. Atmospheric forcing of sea ice in Hudson Bay during the spring period, 1980-2005. Journal of Marine Systems 88:476-487

Jeppesen, E., Nõges, P., Davidson, T. a., Haberman, J., Nõges, T., Blank, K., Lauridsen, T.L., Søndergaard, M., Sayer, C., Laugaste, R., Johansson, L.S., Bjerring, R., and Amsinck, S.L. 2011. Zooplankton as indicators in lakes: a scientific-based plea for including zooplankton in the ecological quality assessment of lakes according to the European Water Framework Directive (WFD). Hydrobiologia 676: 279–297.

Jeziorski A., Yan, N.D., Paterson , A.M., DeSellas, A.M., Turner, M.A., Jeffries, D.S., Keller, W., Weeber, R.C., McNicol, D.K., Palmer, M.E., McIver, K., Arseneau, K., Ginn, B.K., Cumming, B.F., Smol, J.P. 2008. The widespread threat of calcium decline in fresh waters. Science 322: 1374-1377

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G., and Rutka, M.A. 1991. Paleozoic and Mesozoic geology of Ontario *in* Geology of Ontario; Ontario Geological Survey Special Volume 4.

Keller, W. 1993. Relationships between lake morphometry and crustacean zooplankton communities in precambrian Shield lakes. Laurentian University.

Keller W. 2010. Unpublished data. Laurentian University

Keller W., Yan, N.D., Howell, T., Molot, L.A., and Taylor, W.D. 1992. Changes in zooplankton during the experimental neutralization and early reacidification of Bowland Lake near Sudbury, Ontario. Can. J. Fish. Aquat. Sci. 49: 52-62

Keller, W., and Yan, N.D. 1998. Biological recovery from lake acidification: Zooplankton communities as a model of patterns and processes. Restor. Ecol. 6: 364-375

Keller, W., and Conlon, M. 1994. Crustacean zooplankton communities and lake morphometry in Precambrian Shield lakes. Can. J. Fish. Aquat. Sci. 51: 2424–2434.

Keller, W., and Pitblado, J.R. 1984. Crustacean plankton in northeastern Ontario lakes subjected to acid deposition. Water, Air Soil Pollut. 23: 271–291.

Keller, W., and Pitblado, J.R. 1989. The distribution of crustacean zooplankton in northern Ontario , Canada. J. Biogeogr. 16: 249–259.

Keller, W., Yan, N.D., Somers, K.M., and Heneberry, J.H. 2002. Crustacean zooplankton communities in lakes recovering from acidification. Can. J. Fish. Aquat. Sci. 59: 726–735.

Kurek, J., Weeber, R.C., and Smol, J.P. 2011. Environment trumps predation and spatial factors in structuring cladoceran communities from Boreal Shield lakes. Can. J. Fish. Aquat. Sci. 68: 1408–1419.

Lacelle, B. 1997. Canada's soil organic carbon database. In Soil Processes and the Carbon Cycle. Advances in Soil Science. Edited by R. Lal, J.M. Kimble, R.L.F. Follett, and B.A. Stewart. CRC Press, New York. pp. 83–101.

Leavitt, P.R., Carpenter, S.R., and Kitchell, J.F. 1989. Whole-Lake Experiments: The annual record of fossil pigments and zooplankton. Limnol. Oceanogr. 34: 700–717.

Lepš, J., and Šmilauer, P. 2003. Multivariate Analysis of Ecological Data using CANOCO. Cambridge University Press, Cambridge, United Kingdom.

Leverington, D.W., Mann, J.D., and Teller, J.T. 2002. Changes in the bathymetry and volume of glacial Lake Agassiz between 9200 and 7700 14C yr B.P. Quat. Res. 57: 244–252.

Livingstone, D. 1963. Chemical composition of rivers and lakes. United States Department of the Interior, Washington, DC.

MacArthur, R.H., and Wilson, E.O. 1967. The theory of island biogeography. Princeston University Press, Princeton, NJ.

MacPhee S.A., Arnott, S.E., and Keller, W. 2011. Lake thermal structure influences macroinvertebrate predation on crustacean zooplankton. J. of Plankt. Res. 33: 1586-1595

Medeiros, A.S., Biastoch, R.G., Luszczek, C.E., Wang, X.A., Muir, D.C.G., and Quinlan, R. 2012. Patterns in the limnology of lakes and ponds across multiple local and regional environmental gradients in the eastern Canadian arctic. Inl. Waters 2: 59–76.

Moran, M.D. 2003. Arguments for rejecting the sequential Bonferroni in ecological studies. Oikos 100: 403–405.

Neary, B.P., Dillon, P.J., Munro, J.R., and Clark, B.J. 1990. The acidification of Ontario lakes: An assessment of their sensitivity and current status with respect to biological damage.

Oliver, I., and Beattie, A.J. 1996. Invertebrate morphospecies as surrogates for species: A case study. Conserv. Biol. 10: 99–109.

Osterkamp, T.E., and Romanovsky, V.E. 1999. Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafr. Periglac. Process. 10: 17–37.

Palmer, M.E., and Yan, N.D. 2013. Decadal-scale regional changes in Canadian freshwater zooplankton: the likely consequence of complex interactions among multiple anthropogenic stressors. Freshw. Biol. 58: 1366–1378.

Paterson, A.M., Keller, W. (Bill), Rühland, K.M., Jones, F.C., and Winter, J.G. 2014. An exploratory survey of summer water chemistry and plankton communities in lakes near the Sutton River, Hudson Bay Lowlands, Ontario, Canada. Arctic, Antarct. Alp. Res. 46: 121–138.

Pierson, D.C., and Taylor, C.H. 1985. Influence of snowcover development and ground freezing on cation loss from a wetland watershed during spring runoff. Can. J. Fish. Aquat. Sci. 42: 1979–1985.

Pinel-Alloul, B., Methot, G., Verraeult, G., and Vigneault, Y. 1990. Zooplankton species associations in Quebec lakes: Variation with abiotic factors, including natural and anthropogenic acidification. Can. J. Fish. Aquat. Sci. 47: 110–121.

Riley, J.L. 2011. Wetlands of the Hudson Bay Lowlands: a regional overview. The Nature Conservancy of Canada, Toronto, Ontario.

Royal Commission on the Northern Environment. 1985. North of 50: an atlas of far northern Ontario. University of Toronto Press, Toronto, Ontario.

Sandstrom, S., Rawson, M., and Lester, N. 2011. Manual of instructions for broad- scale fish community monitoring using North American gillnets (NA1) and Ontario small mesh gillnets (ON2). Peterborough, Ontario.

Schindler, D.W., Newbury, R.W., Beaty, K.G., and Campbell, P. 1976. Natural water and chemical budgets for a small precambrian lake basin in central Canada. J. Fish. Res. Board Canada 33: 2526–2543.

Sjors, H. 1959. Bogs and fens in the Hudson Bay Lowlands. Arctic 12: 3–19.

Smith, K. and Fernando, C.H. 1978. A guide to the freshwater calanoid and cyclopoid copepod Crustacea of Ontario. University of Waterloo. Department of Biology. Ser. No. 18

Sprules, W.G. 1977. Crustacean zooplankton communities as indicators of limnological conditions : An approach using principal component analysis. J. Fish. Res. Board Canada 34: 962–975.

Stieglitz, M., Shaman, J., McNamara, J., Engel, V., Shanley, J., and Kling, G.W. 2003. An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport. Global Biogeochem. Cycles 17.

Sutey, P., Evans, D., Xu, R., Rusak, J., Jackson, V., Masters, C., and Thomson, C. 2011. User guide for the collection and submission of water samples. Ministry of the Environment – Dorset Environmental Science Centre.

Swadling, K.M., Gibson, J.A.E., Pienitz, R., and Vincent, W.F. 2001. Biogeography of copepods in lakes and ponds of subarctic Quebec.

Symons, C.C., Pedruski, M.T., Arnott, S.E., and Sweetman, J.N. 2014. Spatial, environmental, and biotic determinants of zooplankton community composition in subarctic lakes and ponds in Wapusk national park, Canada

Tarnocai, C. 1997. The amount of organic carbon in various soil orders and ecological provinces in Canada. In Soil Processes and the Carbon Cycle. Advances in Soil Science. Edited by R. Lal, J.M. Kimble, R.L.F. Follett, and B.A. Stewart. CRC Press, New York. pp. 81–92.

Taylor, D.J., Ishikane, C.R., and Haney, R.A. 2002. The systematics of Holactic bosminids and a revision that reconciles molecular and morphological evolution. Limnol. Oceanogr. 47: 1486-1495.

Tessier, A.J., and Horwitz, R.J. 1990. Influence of water chemistry on size structure of zooplankton assemblages. Can. J. Earth Sci. 47: 1937-1943

The Far North Science Advisory Panel. 2010. The report of the Far North Science Advisory Panel. A report submitted to the Ontario Ministry of Natural Resources.

Thorp, J.H., and Covich, A.P. (Editors). 1991. Ecology and classification of North American freshwater invertebrates. Academic Press, Inc., San Diego, California, U.S.A.

Valois, A., Keller, W., and Ramcharan, C. 2010. Abiotic and biotic processes in lakes recovering from acidification: the relative roles of metal toxicity and fish predation as barriers to zooplankton re-establishment. Freshw. Biol. 55: 2585–2597.

Webber, P.J., Richardson, J.W., and Andrews, J.T. 1970. Post-glacial uplift and substrate age at Cape Henrietta Maria, southeastern Hudson Bay, Canada. Can. J. Earth Sci. 7: 317–325.

Webster, N.I., Keller, W.B., and Ramcharan, C.W. 2013. Restoration of zooplankton communities in industrially damaged lakes: Influences of residual metal contamination and the recovery of fish communities. Restor. Ecol. 21: 785-792.

Wetzel, R.G. 2001. Limnology lake and river ecosystems - 3rd Ed. Academic Press – Elsevier Science, San Diego, California, U.S.A.

White, J., Hall, R.I., Wolfe, B.B., Light, E.M., Macrae, M.L., and Fishback, L. 2014. Hydrological connectivity influences seasonal patterns of limnological conditions in shallow tundra ponds of the western Hudson Bay Lowlands. Arctic, Antarct. Alp. Res. 46.

Wilson, M.S. 1959. Calanoida. pp 738-975 in Edmondson, W.T. (ed.) Freshwater Biology. 2nd ed. John Wiley and Sons, Inc., New York.

Wilson, R., and Liu, J. 2012. A GIS assessment of baseline environmental conditions in Ontario's Far North. Niagara-on-the-lake, Ontario.

Woo, M., Marsh, P., and Pomeroy, J. 2000. Snow, frozen soils and permafrost hydrology in Canada, 1995-1998. Hydrol. Proces. 14: 1591-1611

Yan, N.D., Keller, W., MacIsaac, H.J., and McEachern, L.J. 1991. Regulation of zooplankton community structure of an acidified lake by Chaoborus. Ecol. Appl. 1:52-65

Yan, N.D., Somers, K.M., Girard, R.E., Paterson, A.M., Keller, W.B., Ramcharan, C.W., Rusak, J.A., Ingram, R., Morgan, G.E., and Gunn, J.M. 2008. Long-term trends in zooplankton of Dorset, Ontario, lakes : The probable interactive effects of changes in pH, total phosphorus, dissolved organic carbon, and predators. Can. J. Fish. Aquat. Sci. 65: 862–877.

Yeatman, H.C. 1959. Cyclopoida. pp. 796-814 in Edmonson W.T. (ed.) Freshwater Biology. 2nd ed. John Wiley and Sons, Inc., New York.

6 Appendicies

Appendix A: 2011 PCA variable loadings table (Chapter 1, Fig 2-2).

Variable	PC1	PC2	PC3	PC4	PC5
L10Conductivity	0.417	-0.028	-0.188	0.053	-0.150
pH	0.393	-0.140	0.019	-0.040	-0.161
DOC	0.127	0.523	0.210	0.019	0.110
Truecolour	-0.075	0.537	0.049	0.208	0.168
Inorganic N	0.153	-0.111	0.531	0.352	0.124
Total Nitrogen	0.190	0.074	0.585	-0.185	0.111
L10Phosphorus	0.072	-0.167	0.241	0.654	-0.267
Log10ReacSilicon	0.331	0.256	-0.112	-0.096	-0.029
L10Ca	0.420	0.005	-0.158	0.067	-0.184
L10Fe	-0.004	0.486	-0.221	0.274	-0.024
K	0.213	-0.210	0.001	-0.050	0.571
L10Mg	0.426	0.020	-0.149	0.021	-0.102
L10Cl	0.176	-0.105	-0.260	0.234	0.663
L10SO4	-0.200	-0.125	-0.246	0.468	0.016

Appendix B: 2012 PCA variable loadings table (Chapter 1, Fig 2-3).

Variable	PC1	PC2	PC3	PC4	PC5
L10DIC	0.324	0.235	-0.061	-0.023	0.083
DOC	-0.237	0.313	-0.185	0.135	-0.323
L10Cond	0.322	0.245	-0.044	-0.035	0.020
L10TotAlk	0.263	0.137	-0.319	0.085	0.056
pH	0.329	0.128	-0.091	0.074	0.163
Truecolour	-0.240	0.248	-0.064	0.203	-0.474
NTot	-0.200	0.286	-0.047	0.194	0.454
NInorg	-0.008	-0.194	0.303	0.460	0.113
L10PTot	-0.171	0.293	0.170	0.300	0.389
L10Ca	0.288	0.305	-0.124	-0.124	-0.008
L10Cl	0.103	0.160	0.578	-0.347	0.026
L10Mg	0.332	0.170	-0.071	0.142	-0.008
L10K	0.263	-0.199	0.037	0.406	0.046
L10Si	0.258	0.025	0.118	0.240	-0.488
L10Na	0.151	0.176	0.576	-0.034	-0.141
L10Sulphate	0.190	-0.356	0.045	0.335	-0.031
L10Fe	-0.182	0.373	0.142	0.308	-0.057

Appendix C: List of species included in the 2012 ordination analysis

Species	**Abbreviation**
Alona sp.	Alona sp
Ceriodaphnia sp.	Cerio sp
Chydorus sphaericus	Ch Sphaer
Daphnia catawba	Da. cat
Daphnia mendotae	Da. m
Daphnia longiremis	Da. long
Daphnia retrocurva	Da. retr
Holopedium glacialis	Hol glac
Sida crystallina	Sida crys
Eubosmina longispina	E long
Diaphanosoma birgei	Dia birg
Bosmina freyi	B frey
Leptodiaptomus ashlandi	Lepto ashl
Leptodiaptomus minutus	Lepto minu
Skistodiaptomus oregonensis	Skis oreg
Leptodiaptomus sicilis	Lep sicil
Leptodiaptomus siciloides	Lep sicilo
Epischura lacustris	Epi lacus
Diacyclops bicuspidatus thomasi	Cy bi thom
Mesocyclops edax	Meso edax
Tropocyclops extensus	Trop ext

Appendix D: List of species included in the combined analysis (Chapter 2).

Species	Abbreviation
Chydorus sphaericus	Ch sphaer
Daphnia mendotae	Da. m
Daphnia longiremis	Da. long
***Daphnia pulex* complex**	Da. pul (Comp)
Holopedium glacialis	Hol glac
Leptodora kindtii	Lep. Kind
Diaphanosoma birgei	Dia birg
***Bosmina* sp.**	Bos sp
Leptodiaptomus minutus	Lepto minu
Skistodiaptomus oregonensis	Skis oreg
Epischura lacustris	Epi lacus
Diacyclops bicuspidatus thomasi	Cy bi thom
***Acanthocyclops vernalis* complex**	Cyc vern c
Mesocyclops edax	Meso edax
Tropocyclops extensus	Trop ext
***Ceriodaphnia* sp.**	Cerio sp
Daphnia retrocurva	Da. retr
Sida crystallina	Sida crys
Leptodiaptomus ashlandii	Lepto ashl
Leptodiaptomus sicilis	Lep sicil
Daphnia ambigua	Da. amb
Daphnia dubia	Da. dub
Polyphemus pediculus	Pol ped
Onychodiaptomus sanguineus	Ony sang
Limnocalanus macrurus	Limno mac
Senecella calanoides	Sen cal F
Cyclops scutifer	Cyc scut
Camptocercus rectirostris	Cam rec
***Eubosmina* sp.**	Eub sp
Daphnia tenebrosa	Da. tene
***Alona* sp.**	Alona sp
Eubosmina longispina	E. long
Leptodiaptomus siciloides	Lep sicilo

Appendix E: Species richness of 2012 survey lakes (Chapter 2).

Lake name	Species Richness
Ebamet	16
Minimiska	16
Rond	15
Attawapiskat	14
Wigwascence	14
Wildberry	14
Winisk	13
Shamattawa	13
Lang	12
Ozhiski	12
Lingman	12
Totogan	12
Weese	12
Keezhik	11
Troutfly	11
ROF-041	11
Opikeigan	11
I-291	11
No Name 21	11
ROF-063	10
ROF-061	10
ROF-056	10
Leaver	10
Menako	10
Pine	10
Spruce	10
Tutu	10
ROF-050	9
Lingen	9
Duego	9
Goods	8
Wabemieg	8
Muskwabik	8
ROF-065	8
Streatfield	8
Nikip	8
Symons	7
ROF-064	7
Echoing	7
McFauld's	6
ROF-037	6

Appendix F: RDA species loadings for 2012 survey lakes (Chapter 2, Output on Figures 3-3 to 3-4). High values bolded.

Species	**RDA1**	**RDA2**	**RDA3**
Alona.sp	0.0836	-0.1443	**0.4955**
Cerio.sp	-0.0933	**-0.5234**	0.2233
Ch.Sphaer	**-0.4330**	**0.6885**	-0.0691
Da. cat	-0.0084	0.1799	0.1738
Da. m	0.4935	0.1344	0.1200
Da. long	**0.5158**	-0.2396	**-0.5435**
Da. retr	0.3034	-0.2085	0.1239
Hol glac	-0.1361	0.1569	-0.2988
Sida.crys	0.0750	-0.2042	0.1851
E. long	0.4910	0.1899	-0.0922
Dia.birg	0.0213	-0.3553	-0.0846
B. frey	-0.3156	-0.3668	-0.0562
Lepto.ashl	0.3422	0.2096	-0.1685
Lepto.minu	-0.2088	0.1710	-0.3829
Skis.oreg	0.0425	-0.3722	-0.1287
Lep.sicil	0.4224	0.1218	0.0252
Lep.sicilo	0.2524	-0.0016	0.0357
Epi.lacus	0.2259	0.0163	0.3873
Cy.bi.thom	**0.6626**	0.0218	-0.1800
Meso.edax	0.3461	-0.1660	-0.2406
Trop.ext	**-0.4949**	-0.3771	-0.3796

Appendix G: RDA chemistry variable loadings of forward selected variables for 2012 survey lakes (Chapter 2, Output on Figures 3-3 to 3-4). High values bolded.

Variable	**RDA1**	**RDA2**	**RDA3**
Si	**0.6968**	**-0.6564**	0.0319
Fe	-0.3140	-0.0582	**0.8774**
Lake Length	**0.7569**	-0.2335	-0.0593
K	0.4295	**-0.6724**	**-0.5585**
Lake Area	**0.8430**	-0.0815	-0.0960
Si	**0.6968**	**-0.6564**	0.0319

Appendix H: RDA species loadings for combined survey (Chapter 2, Output on Figures 3-6 to 3-8). High values bolded.

Species	RDA1	RDA2	RDA3
Ch sphaer	0.0553	**0.5368**	-0.3213
Da. m	**-0.6766**	-0.0706	**-0.4489**
Da. long	-0.0356	0.2306	-0.2844
Da. pul (Comp)	0.2191	-0.2227	0.3129
Hol glac	**-0.5861**	-0.1058	0.1220
Lep. Kind	0.1965	-0.0655	0.0744
Dia birg	-0.4512	0.4043	0.1267
Bos sp	**0.6513**	0.2845	0.1554
Lepto minu	0.2509	**-0.7573**	0.0217
Skis oreg	-0.3620	0.0059	**0.3221**
Epi lacus	0.4050	0.0525	-0.1212
Cy bi thom	0.2523	-0.2112	**-0.4690**
Cyc vern c	-0.4007	0.0441	0.0726
Meso edax	**-0.8252**	-0.1541	0.2322
Trop ext	-0.4941	0.0339	0.2109
Cerio sp	0.1353	**0.6190**	-0.1091
Da. retr	**-0.7374**	0.1092	0.1963
Sida crys	0.0536	0.2242	-0.0301
Lepto ashl	-0.0983	0.0546	-0.0356
Lep sicil	-0.1641	-0.4539	**-0.6356**
Da. amb	-0.1370	0.0033	0.0897
Da. dub	-0.2048	0.0418	0.1069
Pol ped	-0.2492	-0.0306	-0.0141
Ony sang	-0.0602	-0.2200	-0.1107
Limno mac	-0.2609	-0.2002	-0.2813
Sen cal F	-0.0488	-0.1157	-0.0134
Cyc scut	-0.1037	-0.2586	-0.1201
Cam rec	0.0192	-0.1067	-0.0755
Eub sp	**0.6803**	-0.3284	0.2803
Da. tene	0.3774	-0.0818	0.2503
Alona sp	0.2594	0.3738	-0.1099
E. long	0.0827	0.3656	-0.1390
Lep sicilo	0.0301	0.2423	-0.0422

Appendix I: RDA chemistry variable loadings for combined analysis (Chapter 2, Output on figures 3-6 to 3-8). High values bolded.

Variable	**RDA1**	**RDA2**	**RDA3**
Latitude	**0.8846**	0.3730	0.1290
P	**-0.7051**	**0.5143**	-0.3700
N	0.1067	**0.5599**	**0.6256**
Mg	**0.5358**	0.2696	-0.0263
pH	**0.7982**	0.3582	-0.1936
Lake Area	0.1168	0.2840	**-0.5719**
Longitude	**-0.7727**	-0.0959	-0.2747
Lake Depth	-0.4876	**-0.4643**	**-0.5680**
Na	0.1060	-0.3257	0.0491
K	**-0.6225**	-0.1013	-0.2741
Conductivity	**0.7134**	0.3225	0.0163

Appendix J: Raw chemistry data for 2012 lakes (n=49) (page 1 of 2).

Lake	Survey	Group	Lake Depth (m)	Lake Length (km)	Latitude decimel degrees	Longitude decimel degrees	Carbon; dissolved inorganic mg/L	Carbon; dissolved organic mg/L	Calcium mg/L	Chloride mg/L	Magnesium mg/L	Potassium mg/L	Silicon; reactive silicate mg/L	Sodium mg/L	Sulphate mg/L
ATTAWAPISKAT LAKE	LU/Queens	Shield	10.35	30.49	52.19012	87.75978833	8.84	14.00	12.80	0.17	2.78	0.41	1.24	0.56	0.55
BIG TROUT LAKE	BSM	Shield	39.6	54.24	53.75909	89.912579	13.10	6.40	16.20	0.52	3.03	0.36	1.40	0.50	0.45
BULGING LAKE	BSM	Shield	70	6.41	50.94355	94.94722	2.20	6.80	2.30	0.29	0.98	0.55	0.62	0.77	1.90
CAIRNS LAKE	BSM	Shield	18.5	13.48	51.70542	94.55067	3.48	5.50	3.52	0.20	0.93	0.58	0.08	0.88	1.25
DEUGO LAKE (ROF-008)	LU/Queens	Lowland	2.1	1.71	52.83496	86.48631517	1.92	13.20	3.88	0.27	0.52	0.13	0.10	0.36	0.35
EBAMET LAKE	LU/Queens	Shield	9	30.26	51.51861	87.85114467	10.30	10.90	14.00	0.41	3.12	0.36	0.88	0.50	0.50
ECHOING LAKE	BSM	Shield	30.1	10.12	54.50590	85.039725	29.70	6.00	34.10	1.11	7.92	0.88	2.00	1.45	1.00
GOODS LAKE (ROF-085)	LU/Queens	Shield	3.3	6.22	52.53640	86.7409885	4.26	15.40	7.78	0.31	1.33	0.18	0.80	0.42	0.10
HAGGART LAKE	BSM	Shield	59	8.98	50.87871	94.953401	1.94	7.80	2.16	1.00	0.93	0.54	0.72	0.75	1.75
I-291 LAKE	BSM	Shield	4.2	4.75	51.14079	87.968018	8.48	11.80	11.00	0.19	2.50	0.42	0.12	0.41	0.15
KEEZHIK LAKE	LU/Queens	Shield	17	22.5	51.75379	88.50646567	16.10	7.30	22.20	0.26	4.47	0.64	1.32	0.59	0.90
LANG LAKE	LU/Queens	Shield	5.6	12.96	51.58335	91.50893183	5.48	11.10	8.36	0.10	1.79	0.39	0.72	0.52	0.75
LEAVER LAKE (ROF-013)	LU/Queens	Shield	2	4.04	52.87530	86.75995617	6.66	11.60	9.82	0.25	1.80	0.20	0.28	0.51	0.15
LINGEN LAKE	LU/Queens	Lowland	1.8	5.12	51.91826	85.240304	4.58	14.40	7.72	0.17	1.27	0.17	0.08	0.53	0.25
LINGMAN LAKE	BSM	Shield	5	12.96	53.85397	92.862402	8.16	8.20	10.80	0.37	2.00	0.34	0.60	0.44	0.30
MCFAULDS LAKE (ROF-001)	LU/Queens	Lowland	2	6.04	52.78588	86.05173067	4.64	12.00	7.18	0.28	1.20	0.15	0.04	0.44	0.15
MENAKO LAKE	LU/Queens	Shield	6.5	12.94	52.08465	90.20164767	7.42	11.50	10.80	0.15	2.08	0.37	0.88	0.46	0.40
MINIMISKA LAKE	LU/Queens	Shield	3.3	18.37	51.55641	88.70432833	9.26	11.40	12.70	0.23	2.64	0.46	1.00	0.56	0.70
MUSKWABIK LAKE	LU/Queens	Lowland	1.3	8.67	51.55847	85.05749617	9.28	18.60	13.60	0.18	2.75	0.19	0.56	0.80	0.20
NIKIP LAKE	BSM	Shield	2.7	13.92	52.89665	91.939534	7.64	12.50	9.98	0.17	2.57	0.60	1.42	0.84	0.40
NO NAME 21 LAKE	BSM	Shield	14.6	12.11	53.10013	88.333317	13.20	8.30	16.90	0.50	3.12	0.38	0.40	0.52	0.10
NORTH SPIRIT LAKE	BSM	Shield	31.5	21.36	52.51229	92.961113	5.82	11.50	7.72	0.15	2.06	0.45	1.54	0.72	0.75
OPIKEIGAN LAKE	LU/Queens	Shield	6.6	13.53	51.67412	88.03601367	9.84	11.20	13.30	0.20	2.81	0.38	0.84	0.47	0.40
OZHISKI LAKE	LU/Queens	Shield	12.8	25.89	51.93970	88.60168833	8.62	14.40	12.60	0.22	2.61	0.35	1.24	0.49	0.55
PEEAGWON LAKE	BSM	Shield	1.8	6.35	52.396	88.835004	6.68	10.80	8.40	0.18	1.48	0.22	0.02	0.58	0.15
PINE LAKE	BSM	Lowland	12.7	5.37	54.14640	85.039725	14.10	8.60	28.30	1.23	2.81	0.17	0.78	1.53	0.20
ROF037	LU/Queens	Lowland	1.9	1.56	52.68545	86.61793	1.62	12.00	3.14	0.12	0.49	0.14	0.10	0.33	0.15
ROF041	LU/Queens	Lowland	1.2	1.2	52.70397	86.42279767	2.36	18.60	5.84	0.11	0.84	0.09	0.32	0.42	0.10
ROF050	LU/Queens	Lowland	1.7	1.25	52.72472	85.80543967	2.52	15.30	5.08	0.40	0.84	0.12	0.26	0.50	0.05
ROF056	LU/Queens	Lowland	1.3	3.53	52.70362	85.43716817	6.40	9.80	9.22	0.22	1.41	0.14	0.28	0.53	0.15
ROF061	LU/Queens	Lowland	2	3.62	52.61721	85.45373583	4.26	12.00	6.88	0.21	0.84	0.13	0.08	0.36	0.20
ROF063	LU/Queens	Lowland	2	5.97	52.57082	85.40710833	7.30	12.50	11.60	0.22	1.71	0.18	0.28	0.65	0.20
ROF064	LU/Queens	Lowland	1.6	2.71	52.54091	85.440419	2.52	14.90	4.94	0.19	0.48	0.13	0.02	0.32	0.30
ROF065	LU/Queens	Lowland	1.8	3.13	52.53708	85.48901683	3.70	14.40	7.02	0.15	0.94	0.15	0.14	0.46	0.15
ROND LAKE	LU/Queens	Shield	1.9	2.37	51.62601	88.02402383	10.20	12.10	13.80	0.20	2.92	0.38	0.96	0.48	0.35
SANDY LAKE	BSM	Shield	15.2	86.05	52.99262	93.1914885	8.38	11.50	10.50	0.26	3.22	0.96	1.86	1.24	0.80
SHAMATTAWA LAKE	BSM	Lowland	7.2	13.51	54.16500	85.689167	11.90	15.20	17.20	2.45	2.19	0.13	1.46	2.37	0.10
SPRUCE LAKE	BSM	Lowland	16	6.93	54.33445	85.013606	14.00	7.80	25.30	1.40	2.53	0.18	0.60	1.52	0.25
STREATFIELD LAKE	LU/Queens	Lowland	2.1	6.93	52.13958	85.90295817	6.36	13.30	9.42	0.31	1.86	0.26	0.20	0.75	0.15
SYMONS LAKE (ROF-028)	LU/Queens	Lowland	1.7	2.26	52.54284	86.15889883	6.22	13.00	9.04	0.26	1.82	0.23	0.26	0.59	0.15
TOTOGAN LAKE	BSM	Shield	7	19.35	52.05399	89.180827	9.20	12.20	12.20	0.24	2.60	0.39	1.48	0.53	0.30
TROUTFLY LAKE	LU/Queens	Shield	14.5	8.02	51.70129	88.88412567	23.50	4.90	34.90	0.30	7.30	1.04	1.96	0.90	1.65
TUTU LAKE	BSM	Shield	5.7	3.1	52.07472	92.468177	4.82	7.00	5.44	0.15	1.16	0.74	0.64	0.88	1.05
WABEMEIG LAKE	LU/Queens	Lowland	1.9	11.57	51.47356	85.57454517	4.72	16.90	7.80	0.21	1.57	0.23	0.16	0.59	0.10
WEESE LAKE	BSM	Shield	15	7.26	51.25726	88.622727	13.80	11.50	16.70	0.28	3.91	0.62	1.56	0.50	0.80
WIGWASCENCE LAKE	LU/Queens	Shield	2.9	10.43	52.45509	89.40275183	8.42	12.90	12.30	0.13	2.38	0.47	1.40	0.55	0.45
WILD BERRY LAKE	BSM	Lowland	2.8	12.6	53.98711	86.234092	6.14	14.00	9.52	2.20	1.24	0.15	0.48	1.76	0.05
WINDIGO LAKE	BSM	Shield	7	13.08	52.58991	91.503775	11.60	8.40	14.50	0.20	3.56	0.60	1.90	0.77	0.60
WINISK LAKE	LU/Queens	Shield	2.5	31.84	52.90640	87.38449633	13.90	8.70	19.90	0.36	3.78	0.65	0.68	0.73	0.40

Appendix J: Raw chemistry data for 2012 lakes (n=49) (page 2 of 2).

Lake	Survey	Group	Alkalinity; Gran mg/L CaCO3	pH	Colour; true TCU	Aluminum ug/L	Copper ug/L	Iron ug/L	Nitrogen; ammonia+ ammonium ug/L	Nitrogen; nitrate+ nitrite ug/L	Nitrogen; total Kjeldahl ug/L	Phosphorus; total ug/L	Conductivity uS/cm
ATTAWAPISKAT LAKE	LU/Queens	Shield	41.80	7.65	72.00	36.9	0.80	70.00	26.00	8.00	381.00	10.60	87.60
BIG TROUT LAKE	BSM	Shield	49.30	8.03	9.60			10.00	10.00	2.00	236.00	6.60	114.00
BULGING LAKE	BSM	Shield	8.68	7.19	23.20			10.00	14.00	76.00	249.00	6.40	26.80
CAIRNS LAKE	BSM	Shield	12.90	7.50	8.80			10.00	16.00	2.00	274.00	6.70	33.60
DEUGO LAKE (ROF-008)	LU/Queens	Lowland	11.70	6.99	101.00	30.5	0.20	90.00	18.00	4.00	366.00	12.20	24.80
EBAMET LAKE	LU/Queens	Shield	47.00	7.78	41.00	4.8	0.50	20.00	22.00	2.00	336.00	8.60	96.40
ECHOING LAKE	BSM	Shield	101.00	8.25	5.60			10.00	10.00	2.00	249.00	8.80	232.00
GOODS LAKE (ROF-085)	LU/Queens	Shield	21.40	7.41	93.20	37.0	0.50	130.00	12.00	4.00	371.00	9.20	48.00
HAGGART LAKE	BSM	Shield	7.96	7.17	30.60			101.00	16.00	36.00	294.00	20.20	25.40
I-291 LAKE	BSM	Shield	32.10	7.91	36.60			155.00	22.00	4.00	443.00	8.00	78.20
KEEZHIK LAKE	LU/Queens	Shield	73.50	8.07	15.80	2.8	0.50	10.00	18.00	2.00	261.00	6.40	146.00
LANG LAKE	LU/Queens	Shield	27.20	7.53	52.00	15.4	0.60	40.00	10.00	2.00	325.00	6.60	57.20
LEAVER LAKE (ROF-013)	LU/Queens	Shield	31.10	7.57	41.20	25.1	1.20	60.00	10.00	2.00	470.00	14.60	64.60
LINGEN LAKE	LU/Queens	Lowland	23.20	7.43	92.80	127.0	0.70	210.00	12.00	4.00	348.00	20.60	48.00
LINGMAN LAKE	BSM	Shield	31.20	7.87	24.60			98.00	18.00	2.00	292.00	10.90	74.80
MCFAULDS LAKE (ROF-001)	LU/Queens	Lowland	22.00	7.40	49.60	28.9	0.60	70.00	24.00	4.00	509.00	18.00	46.20
MENAKO LAKE	LU/Queens	Shield	34.70	7.64	55.20	13.6	0.80	90.00	18.00	2.00	347.00	9.80	72.40
MINIMISKA LAKE	LU/Queens	Shield	42.70	7.75	54.00	24.2	0.70	90.00	14.00	4.00	395.00	11.00	89.60
MUSKWABIK LAKE	LU/Queens	Lowland	46.00	7.77	144.00	238.0	0.90	480.00	20.00	4.00	410.00	21.00	93.20
NIKIP LAKE	BSM	Shield	30.50	7.82	71.00			330.00	26.00	4.00	385.00	18.20	75.60
NO NAME 21 LAKE	BSM	Shield	49.10	8.15	17.00			70.00	32.00	36.00	389.00	10.10	119.00
NORTH SPIRIT LAKE	BSM	Shield	23.50	7.71	58.80			164.00	8.00	2.00	316.00	13.10	57.20
OPIKEIGAN LAKE	LU/Queens	Shield	45.90	7.79	43.00	7.3	0.50	40.00	14.00	2.00	364.00	7.20	93.20
OZHISKI LAKE	LU/Queens	Shield	40.90	7.66	86.80	67.9	1.40	190.00	18.00	12.00	408.00	15.40	83.00
PEEAGWON LAKE	BSM	Shield	23.10	7.68	33.40			760.00	6.00	2.00	538.00	53.40	57.20
PINE LAKE	BSM	Lowland	66.30	7.79	34.20			100.00	14.00	2.00	343.00	12.80	137.00
ROF037	LU/Queens	Lowland	9.65	6.94	80.40	25.8	0.80	70.00	12.00	4.00	293.00	9.40	21.20
ROF041	LU/Queens	Lowland	14.40	7.10	155.00	40.8	0.60	140.00	14.00	6.00	384.00	8.00	31.80
ROF050	LU/Queens	Lowland	15.40	7.14	126.00	31.9	0.20	240.00	18.00	6.00	404.00	9.00	32.20
ROF056	LU/Queens	Lowland	29.10	7.56	54.00	21.4	0.40	70.00	14.00	2.00	333.00	15.60	59.60
ROF061	LU/Queens	Lowland	19.20	7.32	60.20	30.3	0.50	60.00	20.00	4.00	503.00	17.20	41.60
ROF063	LU/Queens	Lowland	36.80	7.64	71.80	68.3	0.70	150.00	18.00	4.00	364.00	16.40	73.60
ROF064	LU/Queens	Lowland	14.00	7.13	90.00	45.0	0.50	120.00	14.00	4.00	472.00	20.00	28.80
ROF065	LU/Queens	Lowland	19.60	7.36	119.00	43.7	0.50	230.00	12.00	4.00	299.00	10.80	41.40
ROND LAKE	LU/Queens	Shield	45.70	7.76	48.40	11.9	0.50	60.00	20.00	2.00	380.00	10.60	96.60
SANDY LAKE	BSM	Shield	31.90	7.83	127.00			1434.00	10.00	44.00	368.00	39.40	79.60
SHAMATTAWA LAKE	BSM	Lowland	50.90	7.44	105.00			510.00	18.00	8.00	412.00	11.50	115.00
SPRUCE LAKE	BSM	Lowland	68.00	7.93	31.00			90.00	16.00	2.00	322.00	9.50	133.00
STREATFIELD LAKE	LU/Queens	Lowland	31.30	7.56	83.00	128.0	0.80	260.00	4.00	2.00	447.00	23.40	64.00
SYMONS LAKE (ROF-028)	LU/Queens	Lowland	29.80	7.59	67.40	55.4	0.80	90.00	16.00	2.00	346.00	11.20	61.80
TOTOGAN LAKE	BSM	Shield	36.20	7.89	51.60			140.00	18.00	4.00	394.00	12.30	85.60
TROUTFLY LAKE	LU/Queens	Shield	110.00	8.22	5.20	1.8	0.50	10.00	10.00	2.00	161.00	3.60	214.00
TUTU LAKE	BSM	Shield	18.30	7.62	34.60			179.00	14.00	4.00	256.00	8.40	44.00
WABEMEIG LAKE	LU/Queens	Lowland	23.90	7.38	95.60	145.0	0.70	340.00	2.00	4.00	421.00	25.20	51.00
WEESE LAKE	BSM	Shield	50.30	8.05	50.00			74.00	14.00	2.00	314.00	7.50	119.00
WIGWASCENCE LAKE	LU/Queens	Shield	40.80	7.62	71.60	43.0	0.50	120.00	22.00	2.00	389.00	12.60	81.00
WILD BERRY LAKE	BSM	Lowland	0.95	7.46	74.40			470.00	2.00	2.00	382.00	20.00	68.60
WINDIGO LAKE	BSM	Shield	44.80	8.00	23.80			81.00	18.00	2.00	298.00	11.30	108.00
WINISK LAKE	LU/Queens	Shield	64.20	7.96	19.80	3.8	0.40	30.00	12.00	2.00	360.00	8.60	130.00

Appendix K: Raw zooplankton abundance data for 2012 lakes (calculated # of individuals/m^3) (n=41). Page 1 of 2.

		Ac harp	Alona sp	Cerio sp	Ch Sphaer	Da. cat	Da. m	Da. long	Da. pul	Da. retr	Eury lam	Hol glac	Lat. Setif	Lep. kind	Pol pedic	Sida crys	E. long	Dia birg	Dap sp.	B. frey	B. lied	Grap tes
Lake name	**Survey**	**102**	**109**	**115**	**118**	**120**	**122**	**123**	**124**	**127**	**134**	**135**	**137**	**138**	**142**	**145**	**150**	**152**	**168**	**189**	**190**	**196**
Attawapiskat	**LU/Queens**	0	0	0	80.5	80.5	4266.5	1690.5	80.5	0	0	161	0	0	0	0	724.5	483	241.5	1288	0	0
Duego	**LU/Queens**	0	0	0	490.4	0	0	0	0	0	0	3225.32308	0	0	0	0	75.44615	490.4	0	6940.306	0	0
Ebamet	**LU/Queens**	0	0	362	181	0	2353	1448	0	0	0	362	0	181	0	0	1810	2172	0	6516	181	0
Echoing	**BSM**	0	0	0	0	0	1347.75	1109.91522	0	0	0	118.919488	0	39.63982935	0	0	0	0	0	3805.424	0	0
Goods	**LU/Queens**	0	0	0	18.9	0	6123.6	0	0	0	0	75.6	0	0	0	0	0	113.4	0	321.3	0	0
I-291	**BSM**	0	0	250.592593	676.6	0	200.474	0	0	0	0	300.711111	0	0	0	25.05925926	0	25.059259	0	3759.129	0	0
Keezhik	**LU/Queens**	0	0	0	995.5	0	3348.51	362.004823	0	0	0	1810.00643	0	0	0	0	0	90.496785	0	8147.823	0	0
Lang	**LU/Queens**	0	0	114.983333	689.9	0	3679.47	1609.76667	0	0	0	919.866667	0	0	0	0	0	4254.3833	0	1609.767	0	0
Leaver	**LU/Queens**	0	75.4516837	0	8298.8	0	150.903	37.7258418	0	0	0	2263.55051	0	37.72584184	0	0	0	0	0	4980.13	0	0
Lingen	**LU/Queens**	0	0	0	2546.5	0	641.341	0	0	0	0	1018.6	0	0	0	0	0	37.725926	0	7091.718	0	0
Lingman	**BSM**	1.9577778	0	45.0288889	352.4	0	0	0	0	5.8733333	0	0	0	0	1.957777778	0	0	11.746667	0	8018.203	1.957778	0
McFauld's	**LU/Queens**	0	0	0	198494.9	0	181.074	0	0	0	0	633.757264	0	0	0	0	0	0	0	995.9043	0	0
Menako	**LU/Queens**	0	0	0	1317.1	0	8429.44	790.26	0	0	0	131.71	0	0	0	0	0	263.42	0	2634.2	0	0
Minimiska	**LU/Queens**	0	0	17.6666667	10.6	0	120.133	3.53333333	0	98.933333	0	56.5333333	0	0	0	28.26666667	3.533333	56.533333	0	137.8	0	0
Muskwabik	**LU/Queens**	0	0	215.333333	17	0	0	0	0	17	0	0	0	0	0	51	0	85	0	2002.222	0	0
Nikip	**BSM**	0	0	3.91428571	13.7	0	0	0	0	0	0	1.95714286	0	1.957142857	0	0	0	0	0	511.4667	0	0
No Name 21	**BSM**	0	0	191.85	383.7	0	164.443	438.514286	0	0	0	191.85	0	0	0	0	0	191.85	0	1699.243	0	0
Opikeigan	**LU/Queens**	0	0	0	1287.6	0	19926.1	643.8	0	1931.4	0	643.8	0	0	0	0	0	1931.4	0	24625.35	0	0
Ozhiski	**LU/Queens**	0	4.7	9.4	4.7	14.1	1453.71	0	0	764.53333	0	0	0	0	0	0	0	14.1	0	47	0	0
Pine	**BSM**	0	0	0	186	0	1195.66	0	0	0	0	0	0	79.71428571	0	0	0	199.28571	0	199.2857	0	0
ROF-037	**LU/Queens**	0	0	0	1226.1	0	0	0	0	0	0	203.721231	0	0	0	0	0	0	0	3998.546	0	0
ROF-041	**LU/Queens**	0	0	188.666667	113.2	0	0	0	0	0	0	37.7333333	0	0	0	0	150.9333	37.733333	0	245459.2	2547	0
ROF-050	**LU/Queens**	0	0	0	42.4	749.06667	127.2	0	0	0	0	42.4	0	0	0	0	0	7.0666667	0	289.7333	0	0
ROF-056	**LU/Queens**	0	0	28.2947917	2716.3	0	226.358	0	0	0	0	56.5895833	0	0	0	0	0	0	0	3508.554	0	0
ROF-061	**LU/Queens**	0	9.4315144	0	17804.8	0	207.493	0	0	0	0	245.219374	0	9.431514395	0	0	0	0	0	15692.37	94.31514	0
ROF-063	**LU/Queens**	0	0	0	1075.2	28.294737	18100.5	0	0	0	0	0	0	141.4736842	0	0	0	0	0	311.2421	0	0
ROF-064	**LU/Queens**	0	0	0	52464.3	0	75374.8	0	0	0	0	452.85755	0	0	0	0	0	1358.5727	0	7245.721	0	0
ROF-065	**LU/Queens**	0	0	0	14787	0	6337.29	0	0	0	0	150.887755	0	0	0	0	0	301.77551	0	13579.9	0	0
Rond	**LU/Queens**	0	4.71666667	0	56.6	0	179.233	0	0	14.15	0	14.15	0	0	4.716666667	42.45	0	4.7166667	0	318.375	0	0
Shamattawa	**BSM**	1.9585366	29.3780488	15.6682927	80.3	0	0	0	7.8341463	0	0	33.295122	0	0	3.917073171	1.958536585	0	0	0	485.7171	0	3.91707317
Spruce	**BSM**	0	9.61666667	0	57.7	0	2346.22	0	0	0	0	0	0	9.616666667	0	0	0	0	0	182.7167	0	0
Streatfield	**LU/Queens**	0	0	0	415	0	18.8636	0	0	0	0	0	0	0	0	0	0	943.18182	0	264.0909	0	0
Symons	**LU/Queens**	0	0	0	124.5	441.40909	0	0	0	0	0	124.5	0	0	0	0	0	67.909091	0	707.3864	0	0
Totogan	**BSM**	0	0	0	2380	0	32074.2	0	0	0	0	125.263158	0	125.2631579	0	0	0	1878.9474	0	2630.526	0	0
Troutfly	**LU/Queens**	0	0	0	57.5	0	57.5	805	0	0	0	0	0	0	0	0	0	57.5	0	3815.749	0	0
Tutu	**BSM**	0	0	344.583608	0	0	31.3258	0	0	0	0	31.3257825	0	0	0	0	0	2338.7423	0	3571.139	0	0
Wabemieg	**LU/Queens**	0	0	0	1160.1	0	0	0	0	424.42683	56.5902439	56.5902439	0	0	0	0	0	339.54146	0	5161.361	0	0
Weese	**BSM**	0	0	0	0	0	13.9032	536.267139	0	0	0	13.9032221	1.986174588	0	0	0	0	0	0	345.5944	0	0
Wigwascence	**LU/Queens**	0	20.5666667	308.5	61.7	0	267.367	0	0	781.53333	0	20.5666667	0	0	0	0	82.26667	534.73333	0	8143.768	0	0
Wildberry	**BSM**	0	7.8315	23.4945	1566.3	0	5345.73	0	0	0	0	0	0	0	0	15.663	0	62.652	0	31.326	0	0
Winisk	**LU/Queens**	0	0	0	6236.7	0	10182.8	2615.39032	0	804.73548	0	1005.91935	0	0	0	0	0	1005.9194	0	3621.31	0	0

Appendix K: Raw zooplankton abundance data for 2012 lakes (calculated # of individuals /m^3) (n=41). Page 2 of 2.

		Cal copep	Lepto ashl	Lepto minu	Skis oreg	Lep sicil	Lep sicilo	Epi lacus	Ep lac cp	Cal naup	Cyc copep	Cy bi thom	Cyc vern c	Eucy agil	Mac albid	Meso edax	Cycl naup	Trop ext	Harp naup	Harp sp	Eub sp
Lake name	**Survey**	**201**	**202**	**204**	**205**	**208**	**209**	**210**	**211**	**215**	**301**	**302**	**304**	**306**	**308**	**309**	**313**	**338**	**344**	**345**	**653**
Attawapiskat	**LU/Queens**	9650.117647	0	0	80.5	1127	0	0	241.5	9248.029412	6039.046095	1529.5	0	0	0	724.5	16931.00769	0	0	0	0
Duego	**LU/Queens**	1018.523077	0	679.0153846	0	0	0	0	528.1230769	3846.522959	1923.876923	0	0	0	0	0	3771.905356	37.7230769	37.72307692	0	0
Ebamet	**LU/Queens**	45111.47959	2715	362	0	0	0	0	1086	3849.204866	14020.32481	5973	1086	0	0	543	32480.26531	0	0	0	0
Echoing	**BSM**	14221.8	0	0	0	0	0	0	0	79.2796587	10429.32	1823.43215	0	0	0	0	12325.56	0	0	0	0
Goods	**LU/Queens**	94.5	0	0	737.1	0	0	113.4	2268	9982.394366	1814.4	642.6	0	0	0	0	1814.4	0	0	0	0
I-291	**BSM**	1253.043153	0	0	75.17777778	0	0	0	25.05925926	1190.390995	2318.129832	0	0	0	0	0	563.8694187	576.362963	0	0	0
Keezhik	**LU/Queens**	181.0024114	0	181.0024114	271.4991962	0	0	0	1086.005627	1924.61506	17142.45182	2986.517684	0	0	0	0	27067.01802	181.002411	0	0	0
Lang	**LU/Queens**	29018.25538	0	1494.783333	229.9666667	0	0	0	6842.759752	3620.31977	10867.91255	1264.816667	0	0	0	0	8050.305591	689.9	0	0	0
Leaver	**LU/Queens**	37.72584184	0	0	0	0	0	0	0	37.72584184	27206.13594	377.2584184	75.45168368	0	0	0	15849.92555	188.629209	0	0	0
Lingen	**LU/Queens**	75.45185185	0	37.72592593	75.45185185	0	0	0	1697.666667	18995.63086	27136.61552	1018.6	0	0	0	0	27206.19658	0	0	0	0
Lingman	**BSM**	33.28222222	0	0	1.957777778	0	0	0	0	117.4666667	1440.924444	5.873333333	0	0	0	0	7510.656436	25.4511111	0	3.9155556	0
McFauld's	**LU/Queens**	3395.345489	0	497.9521362	0	0	0	0	1924.029111	28945.82685	1018.603647	0	0	0	0	0	9962.86822	0	0	0	0
Menako	**LU/Queens**	3126.911689	0	0	0	0	1843.94	0	526.84	4772.654683	5595.52618	1975.65	0	0	0	0	15131.15471	131.71	0	0	0
Minimiska	**LU/Queens**	14.13333333	0	3.533333333	7.066666667	0	0	24.73333333	7.066666667	3843.036895	961.0666667	21.2	3.533333333	0	0	3.533333333	6103.646833	0	0	0	0
Muskwabik	**LU/Queens**	0	0	0	0	0	0	0	11.33333333	90.66666667	1530	396.6666667	0	0	0	0	4758.477287	0	0	0	0
Nikip	**BSM**	0	0	0	0	0	0	0	0	27.4	23.48571429	0	1.957142857	0	0	0	70.45714286	0	0	3.9142857	0
No Name 21	**BSM**	1754.057143	0	82.22142857	137.0357143	0	0	0	0	520.7357143	1479.985714	109.6285714	0	0	0	0	1699.242857	164.442857	0	0	0
Opikeigan	**LU/Queens**	3219	0	0	7403.7	0	0	0	1931.4	3862.8	8208.45	965.7	0	0	0	7725.6	13749.49335	0	0	0	0
Ozhiski	**LU/Queens**	0	0	0	4.7	0	0	79.9	14.1	1127.639155	1503.518874	216.2	0	4.7	0	0	12653.84615	0	0	0	0
Pine	**BSM**	26.57142857	0	0	186	0	0	186	13.28571429	315.5559086	1993.622645	757.2857143	0	0	0	0	5044.052247	0	53.14285714	0	0
ROF-037	**LU/Queens**	33.95353846	0	11.31784615	0	0	0	0	181.0855385	10415.7515	962.0169231	0	0	0	0	0	4073.121217	373.488923	0	0	0
ROF-041	**LU/Queens**	603.7333333	0	113.2	0	0	0	0	301.8666667	377.3333333	10870.67862	0	0	0	0	0	36282.05128	1207.46667	75.46666667	0	0
ROF-050	**LU/Queens**	56.53333333	0	42.4	0	0	0	35.33333333	763.2	3278.933333	565.3333333	0	0	7.066666667	0	0	678.4	0	0	0	0
ROF-056	**LU/Queens**	820.5489583	0	141.4739583	84.884375	0	0	0	707.3697917	1188.38125	6639.13627	169.76875	28.29479167	0	0	0	8151.508483	0	0	0	0
ROF-061	**LU/Queens**	410.2708762	0	160.3357447	0	0	0	0	9.431514395	2150.385282	37.72605758	9.431514395	0	0	0	0	3846.826889	0	0	0	0
ROF-063	**LU/Queens**	141.4736842	0	452.7157895	0	0	0	0	565.8947368	7245.771278	2489.936842	848.8421053	28.29473684	0	0	0	5204.566118	56.5894737	0	0	0
ROF-064	**LU/Queens**	24641.76103	0	18114.302	0	0	0	0	0	15377.46724	15850.01425	1811.4302	0	0	0	0	57743.95862	0	0	0	0
ROF-065	**LU/Queens**	2565.091837	0	905.3265306	0	0	0	0	4526.632653	9810.843217	1056.214286	1056.214286	0	0	0	0	18710.08163	0	0	0	0
Rond	**LU/Queens**	42.45	0	0	174.5166667	0	0	0	51.88333333	481.1	254.7	14.15	0	0	0	108.4833333	1132	4.71666667	0	0	4.716667
Shamattawa	**BSM**	5.875609756	0	0	0	0	0	0	13.7097561	250.6926829	19.58536585	0	0	0	0	0	133.1804878	0	0	3.9170732	0
Spruce	**BSM**	38.46666667	0	86.55	28.85	0	0	221.1833333	57.7	288.5	16559.31122	1923.1282	0	0	0	0	20239.15816	0	0	0	0
Streatfield	**LU/Queens**	113.1818182	0	18.86363636	603.6363636	0	0	56.59090909	113.1818182	1584.545455	5657.280579	3338.863636	0	0	0	0	6336.154249	0	0	0	0
Symons	**LU/Queens**	1471.363636	0	475.3636364	0	0	0	0	45.27272727	24423.82585	79.22727273	0	0	0	0	0	377.2727273	0	0	0	0
Totogan	**BSM**	49945.48872	0	626.3157895	626.3157895	0	0	125.2631579	4258.947368	16064.51822	23092.74494	3507.368421	0	0	0	125.2631579	1002.105263	0	0	0	0
Troutfly	**LU/Queens**	345	0	1940.211132	230	0	0	0	460	6980.294118	12959.61538	1782.5	0	0	0	115	15551.53846	0	0	0	57.5
Tutu	**BSM**	156.6289127	0	0	156.6289127	0	0	0	939.7734764	3507.365288	3006.313104	62.65156509	187.9546953	0	0	0	11016.1	469.886738	0	0	0
Wabemieg	**LU/Queens**	0	0	0	0	0	0	28.29512195	622.4926829	4978.348392	6562.368335	367.8365854	0	0	0	0	7693.811151	0	0	0	0
Weese	**BSM**	33.764968	0	5.958523765	9.930872941	0	0	1.986174588	5.958523765	101.294904	1191.704753	67.529936	0	0	0	17.87557129	1620.2	9.93087294	0	0	0
Wigwascence	**LU/Queens**	123.4	0	20.56666667	20.56666667	0	41.13333333	0	164.5333333	361.9838635	2714.58942	164.5333333	0	0	0	0	6785.026232	0	0	0	20.56667
Wildberry	**BSM**	31.326	0	46.989	70.4835	0	0	7.8315	54.8205	23.4945	845.802	125.304	54.8205	0	7.8315	0	180.1245	0	0	0	0
Winisk	**LU/Queens**	2213.022581	0	201.183871	201.183871	0	0	0	4978.238895	15377.44544	14472.88983	5431.964516	0	0	0	0	33798.89032	201.183871	0	0	201.1839

Appendix L: Dissolved oxygen and temperature profiles for 2012 survey lakes

Kheezik Lake - July 11 2012 1:20pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	21.6	8.85	100.3
1	21.6	8.87	100.4
2	21.4	8.86	100.2
3	21.4	8.81	99.6
4	21.2	8.8	99.1
5	20.9	8.81	98.6
6	20.3	8.96	99.1
7	19.5	8.42	91.6
8	19.2	8.21	88.8
9	19	7.92	85.2
10	18.8	7.62	81.7
11	18.2	7.28	77.2
12	17.5	7.89	72.2
13	16.2	5.59	56.8
14	14.3	2.21	21.6
15	12.6	0.15	1.4
16	12.1	0.09	0.8

Troutfly - July 11th 2012 2:55pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	21	8.55	95.8
1	20.9	8.54	95.7
2	20.6	8.71	97
3	20.1	8.79	96.8
4	19.8	8.84	96.8
5	19.6	8.91	97.3
6	19.4	8.99	97.7
7	19.1	9.07	97.9
8	18.9	9.23	99.4
9	18.8	9.24	99
10	17.9	8.86	93
11	16.4	8.11	82.9
12	15.5	7.27	72.9
13	15.3	6.54	65.1
14	14.9	5.29	52.3

Attawapiskat - July 11th 2012 4:45pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	20.9	7.9	88.4
1	20.9	7.91	88.4
2	20.8	8.01	89.4
3	20.7	7.9	88.1
4	20.4	7.72	85.7
5	20.4	7.69	85.2
6	20.4	7.66	84.9
7	20.3	7.57	83.9
8	19.7	7.23	78.9
9	19.4	7.23	78.6
10	19.2	7.05	76.3

ROF-063 - July 12th 2012 9:43am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	21.8	9.19	104.6
1	21.1	9.19	103.2
2	20.6	4.5	46

ROF-061 - July 12th 2012 10:53am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	21.9	8.6	98.1
1	21.7	8.5	96.6
1.9	20.9	7.75	87

ROF-050 - July 12th 2012 12:11pm

Depth	Temp (oC)	DO (mg/L)	DO (%)	
0	22.6	7.8	90	
1	22	7.82	89.5	
1.8	21.6	3-6.5	37-70	Unable to equalize

McFaulds (ROF-001) - July 12th 2012 12:55pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23.1	8.31	97.3
1	22.3	8.28	95.2
2	21.5	8.25	93.7

Symons (ROF-028) - July 12th 2012 2:21pm

Depth	Temp (oC)	DO (mg/L)	DO (%)	
0	25.1	7.98	96.3	
1	23.1	8.08	95.1	
1.8	22.3	0.4-4.2	4-46%	Unable to equalize

ROF-037 July 12th 2012 3:32pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23.8	7.83	92.5
1	23.8	7.87	93
1.8	22.7	7.81	90.5

Goods (ROF-085) July 12th 2012 approx 4:45pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	22.5	8.31	96
1	22.5	8.31	95.9
2	22.3	8.33	95.7
3	21.5	8.15	91.2

Wabemieg July 13th 2012 9:40am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23	8.58	100
1	22.9	8.51	99
1.9	22.8	8.46	98.2

Muskwabik July 13th 2012 10:12am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23.7	8.19	
1	23.7	8.19	
2	23.6	8.5	

Lingen Lake July 13th 2012 11:03am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23.5	8.53	
1	23.4	8.42	
1.7	23.4	8.05	

ROF-065 July 13th 2012 11:58am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	22.8	8.37	
1	22.8	8.37	
1.5	22.7	8.38	

ROF-064 July 13th 2013 1:11pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	24	8.71	
1	24	8.72	

ROF-056 July 13th 2012 1:44pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	24.2	8.45	
1	24.2	8.4	

Streatfield July 13th 2012 2:46pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	24	8.51	
1	23.9	8.49	
1.5	23.8	8.45	

Winisk July 14th 2012 11:47am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	20.9	9.08	102.8
1	20.9	9.13	102.2
2	20.9	9.11	102

Leaver (ROF-013) July 14th 2012 12:58pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23.7	7.79	92.5
1	23.7	7.41	87.4
2	23.6	7.38	87

Deugo (ROF-008) July 14th 2012 1:41pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	23.1	7.35	85.9
1	23.1	7.36	85.9
2	23	7.36	85.8

ROF-041 July 14th 2012 2:18pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	24.8	7.1	85.7
1	24.8	7.05	85

Ebamet July 15th 2012 8:51am

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	21.7	8.16	92.4
1	21.6	8.11	91.8
2	21.6	8.12	92.2
3	21.6	8.13	92.4
4	21.6	8.11	92.2
5	21.6	8.1	92.1
6	21.1	7.96	89.3
7	20.6	7.87	87.6
8	19.9	7.67	84.3
8.5	18.7	6.88	74.2

Lang July 15th 2012 12:22pm

Depth	Temp (oC)	DO (mg/L)	DO (%)
0	24	7.87	93.6
1	23.7	7.93	93.5
2	23.1	7.89	92.3
3	23	7.84	91.5
4	22	7.34	84.2
5	20.8	6.98	78

Note: Not all lakes were sampled because the DO/temperature probe was not functioning on the last day of sampling.

Appendix M: 2012 DOM spectrometry data (n=29)

Lake	HIX	FI	SUVA	BA	E2E3
Attawapiskat	13.59983	1.42216	4.01919	0.48399	3.86979
Deugo	11.20987	1.35114	4.54177	0.42583	3.45467
Eabemet	10.87426	1.40360	3.82089	0.52837	3.77816
Goods	17.21276	1.33185	4.40987	0.44175	3.94806
Keezhik	5.04362	1.33107	3.14037	0.58663	3.02303
Lang	10.73719	1.30285	4.08141	0.49204	3.75016
Leaver	8.06469	1.42713	3.22890	0.51697	3.64385
Lingen	10.96479	1.37188	3.87341	0.46613	3.64800
McFauld's	8.70200	1.35822	3.04398	0.49830	3.47618
Menako	12.04964	1.34920	4.07409	0.49636	3.79903
Minimiska	10.83130	1.41288	3.84985	0.49760	3.66723
Muskwabik	17.90053	1.32592	4.29049	0.41591	3.96759
Opikeigan	10.90185	1.31306	3.60188	0.49838	3.68961
Ozhiski	14.54174	1.35530	4.07398	0.46734	3.87877
ROF-037	12.29618	1.30152	4.34859	0.41913	3.46309
ROF-041	16.63466	1.34029	4.74455	0.38432	3.80041
ROF-050	15.77435	1.36543	4.67279	0.40200	3.53919
ROF-056	8.02563	1.25157	3.80731	0.50883	3.28060
ROF-061	6.88044	1.31985	3.25638	0.48211	3.41715
ROF-063	11.19821	1.34869	3.80546	0.44312	3.64343
ROF-064	10.88352	1.32707	3.43738	0.44836	3.51041
ROF-065	14.50795	1.36813	4.62996	0.39782	3.52511
Rond	10.52309	1.28754	3.46815	0.49976	3.80602
Streatfield	10.89907	1.34316	3.97056	0.47984	3.77053
Symons	11.46822	1.39722	3.86072	0.47841	3.68310
Troutfly	2.57503	1.22212	3.07280	0.71566	2.21804
Wabemieg	10.69601	1.40547	3.70620	0.41683	4.04631
Wigwascense	11.65252	1.32330	4.36302	0.47731	3.88374
Winisk	7.13925	1.38714	2.98381	0.60706	3.37489

HIX: humification index (ratio)
FI: fluorescence index (ratio)
SUVA: 254nm absorbance (ratio)
BA: beta:alpha, freshness index (ratio)
E2E3: absorbance (ratio)

Appendix N: 2012 raw hydrology isotope data

Lake	Sample Date	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰
Attawapiskat	11-Jul-12	-12.2707	-93.4141
Deugo	14-Jul-12	-8.6679	-79.4671
Ebamet	15-Jul-12	-11.5361	-90.9893
Goods	12-Jul-12	-12.7537	-93.7180
Keezhik	11-Jul-12	-10.3334	-85.4224
Lang	15-Jul-12	-10.1778	-84.8286
Leaver	14-Jul-12	-9.5833	-83.9888
Lingen	13-Jul-12	-10.0650	-80.7792
McFaulds	12-Jul-12	-9.8676	-80.8606
Menako	15-Jul-12	-12.0452	-92.0945
Minimiska	15-Jul-12	-10.0132	-83.8863
Muskwabik	13-Jul-12	-11.3988	-87.6201
Opikeigan	15-Jul-12	-10.8908	-88.0260
Ozhiski	15-Jul-12	-10.7243	-85.4695
ROF - 037	12-Jul-12	-10.2951	-83.7517
ROF - 041	14-Jul-12	-11.2100	-89.6259
ROF - 050	12-Jul-12	-11.4347	-84.6784
ROF - 061	12-Jul-12	-9.2720	-77.7353
ROF - 063	12-Jul-12	-11.0186	-84.7642
ROF - 064	13-Jul-12	-9.1844	-76.8903
ROF - 065	13-Jul-12	-10.9023	-85.4688
ROF - 56	13-Jul-12	-10.2656	-83.0280
Rond	15-Jul-12	-11.5200	-90.1169
Streatfield	13-Jul-12	-10.3657	-83.5289
Symons	12-Jul-12	-11.0081	-84.9052
Troutfly	11-Jul-12	-10.6868	-86.7384
Wabemieg	13-Jul-12	-10.5435	-84.3522
Wigwascense	15-Jul-12	-11.7518	-92.4680
Winisk	14-Jul-12	-11.1088	-88.9221