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Causes And Consequences Of Changes In Algal Community Structure Of Arctic Tundra Ponds From Barrow, Alaska

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CAUSES AND CONSEQUENCES OF CHANGES IN ALGAL COMMUNITY STRUCTURE
OF ARCTIC TUNDRA PONDS FROM BARROW, ALASKA.

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2011

Dedication

This thesis is dedicated first to my lovely husband and my cute daughter who have provided me with incredible support and, most importantly, represented unconditional love in my life. Also, to my parents Javier Vargas Z. and Socorro Medrano C. for teaching me and encouraging me to always work hard to make all my dreams possible and for making me the person I am today. To my siblings Dr. Javier Vargas M. and Marisela Vargas for the love and support that they provided to me, and to their families for allowing that to happen.

To my friends and professors at UTEP for their dedication and support, especially my advisor Vanessa, her husband Craig and, of course, Dr. Gonzalez, the undergraduate lab coordinator. Also, to my lab mates and friends Gabriela Contreras, Fernanda De la Cerda, Christina Hernandez, Christian Andersen, Anibal Sierra and Frankie Reyes.

To all the scientists that dedicated their lives to research to improve human-kind's quality of life or to understanding earth processes in order to be able to predict future changes and prepare humanity to address future changes. Especially to all the researchers in Barrow during the 1970s, who dedicated a lot of time to develop many research projects. Finally, I will say thank you to God for the many blessings that he has always provided to my life.

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OF ARCTIC TUNDRA PONDS FROM BARROW, ALASKA.

by

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Abstract

Algal communities in the Arctic are highly sensitive to environmental change, such as longer growing seasons and changes in ice cover. On the north slope of Alaska, ponds and lakes cover large portions of the total land area. We surveyed the periphytic algal communities in tundra ponds from Barrow, Alaska to assess environmental effects on their populations. Samples were collected in August 2008-10 from two main study areas: the IBP (the International Biological Program), which was also studied in 1970-71 but now is located near to human settlements, and the BEO (Barrow Environmental Observatory), which is within a protected area. The algal community composition in the IBP ponds has changed dramatically over the past 40 years, with many new taxa observed in the recent samples. However, gross taxonomic composition in IBP Pond B was somewhat similar between 2010 and 1972. The dominant algal groups in 2008-10 were Cyanophyta and Bacillariophyceae. Cyanophyta tended to dominate under low nutrient, high light conditions in the spring and early summer, whereas, Bacillariophyceae dominated when nutrient levels were highest in late summer. Moreover, these two algal groups fluctuated in relative abundance twice during the growing season. We also found some algal taxa at some sites that were bioindicators of nutrient-rich conditions, but they were rather low in relative abundance; however, we recommend paying attention to these species because they may be important pollution indicators in the future. It is important to understand algal processes in aquatic ecosystems in the Arctic, since any change in the primary producers can cause a cascading effect on the whole ecosystem and have impacts for global carbon balances.

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1. Introduction

Algae are often the dominant primary producers in aquatic ecosystems. Understanding their response to environmental change is important because any change in the algal community can affect organisms at higher trophic levels (Brow and Wright, 2009). In aquatic environments, algae can be found in two primary habitats: the open water and attached to various surfaces. Algae found in the open water are generally referred to as phytoplankton, while periphyton are those algae that may be found attached to nearly any submerged surface. Depending on the surface that algae are attached to, periphyton receive different names such as epilithon (attached to rock), epipelon (attached to mud or silt), episammon (attached to sand), and epiphyton (attached to submerged portions of aquatic macrophytes) (Cronk and Fennessy, 2001). Because of their sensitivity to environmental change, algae are often used as indicators of changing aquatic conditions, particularly water quality. Some groups of algae are more frequently used as bioindicators, largely because of their ability to be preserved in lake sediments. For example, the siliceous cell walls of Bacillariophyceae (Douglas et al., 1994) and the stomatocysts and scales of Chrysophyceae (Smol, 2002) allow the preservation of these taxa in lake sediments and their use in paleolimnological studies to reconstruct past environmental conditions (Dixit et al., 1992, Rühland et al., 2003b); this is especially useful in the absence of long-term monitoring of environmental variables (Pienitz et al., 2004).

The tundra biome is characterized by cold winters, cool summers, low levels of precipitation and snow cover for 7-9 months each year. Soil remains continuously frozen in permafrost, with only the surface, or the active layer, thawing each summer. Ponds and lakes are important in the Arctic tundra, covering a large percentage of the total land area (Hinkel et al. 2003; Frohn et al. 2005). These shallow arctic ponds freeze to the bottom every winter, have only a few months of open water, and are characterized by

circumneutral pH, low ions and dissolved gases near saturation (Sheath, 1986). Ponds are formed by a cyclic process that starts with ice-wedges forming and delimiting low-centered flooded polygons in a drained lake basin. With the passing of many years and the thawing of permafrost, the ponds fuse to form shallow lakes, which eventually drain with further permafrost thaw (Stanley, 1976; Sheath, 1986).

All Arctic subregions are considered highly sensitive to climate change (Smol et al., 2005) and data from this environment are particularly valuable (Hobbie, 1980). Recently in the Arctic the climate has been warming (Rothrock and Zhang, 2003; Smol et al., 2005) resulting in permafrost thaw, the release of CO₂ and other gases to the atmosphere (Vogel et al., 2009), and an increase in precipitation and temperature during the winter (Douglas et al., 1994). Various ecosystem components have also been changing, including terrestrial vegetation composition (Euskirchen et al., 2009), microbial biomass (Frey et al., 2008), and aquatic community structure (Smol et al., 2005). In aquatic environments, paleolimnological studies reported changes in algal composition as a response to the reduction in ice cover, changes in thermal stratification, a prolongation of the growing season, decreased pond size and changes in pH (Psenner and Schmidt, 1992; Douglas and Smol, 1999; Douglas and Smol, 2001; Rühland et al., 2003b; Smol et al., 2005). Specifically the decrease in ice cover is linked with changes in primary production (Douglas, 1999). Many of these algal community changes correspond to a period of high anthropogenic disturbance and warming beginning at the turn of the 19th century (Douglas et al., 1994).

Research completed forty years ago, at the International Biological Program (IBP) tundra biome site in Barrow, Alaska, is one of the rare examples of detailed historical data on aquatic production in the Arctic (Hobbie et al., 1980). Loughheed et al. (submitted) found that the IBP ponds are warmer, more nutrient rich and have greater macrophyte cover than existed in the 1970s. This project will add to these preliminary results and capitalize on these invaluable historic data by comparing algal communities

from ponds in Barrow Alaska in 2008-10, with historical data published by Stanley et al. (1976) and Alexander et al. (1980). In these studies, they measured photosynthetic rate, algal biomass, algal composition, productivity rate and solar radiation in order to better understand the processes affecting primary production in arctic tundra ponds. Epipellic (sediment-associated) algal composition was studied in mid-July 1972 in ponds B and E (as well as experimental sub-ponds B4-12). The dominant algae were Chlorophyta (green algae) and Cyanophyta (blue-green algae), which represented more than 90% of the algal biomass in pond B and more than 60% in pond E. Bacillariophyceae (diatoms) were also relatively abundant in pond E. The most common genera in Pond B were *Microcystis*, *Gomphonema*, *Aphanizomenon*, *Chlamydomonas*, *Closterium*, and *Ankistrodesmus* (Stanley, 1976). Although Pond E received an experimental oil spill treatment in July 1970 (Miller et al., 1978) and thus showed low epipellic productivity in 1971, the algal community recovered by 1972 when the algal composition was similar to nearby ponds. In addition to these data on taxonomic composition, phosphorus enrichment experiments on another pond (Pond D) indicated that photosynthetic rates and algae biomass were limited by phosphorus (Alexander et al., 1980). When phosphorus was added to the ponds, nitrogen became limiting and enhanced the growth of nitrogen-fixing Cyanophyta in the sediment (Alexander et al., 1980).

The Polar Regions have been affected by the deposition and input of various persistent organic pollutants and other anthropogenic compounds, such as acid precipitation, nutrients, and heavy metals. For example, organochlorines, such as PCBs, have been transported from industrialized regions to northern areas through global air patterns and cold condensation. These compounds persist in Polar Regions because the low temperatures inhibit the breakdown of molecules (Paterson et al., 2002). Nevertheless, some studies revealed that the concentrations of PCBs and persistent organic pollutants (POPs) were low and, even in high concentrations, did not have any considerable effect on

phytoplankton communities (Rühland et al., 2003a; Wania and Mackay, 1993; Paterson et al., 2002). Localized human activities, including urban development, can also contribute pollution to aquatic systems through both point and non-point sources (Lougheed et al. 2001), and this could be a concern for the IBP ponds, which are currently being encroached upon by the growing village of Barrow, AK. However, studies in Arctic and subarctic regions indicated that climate change caused more change in algal community composition than airborne pollution, elevated UV radiation, nutrient enrichment, and anthropogenic acidification (Smol et al., 2005; Paterson et al., 2002; Rühland et al., 2003b). Nonetheless, diatom communities in the relatively small Arctic ponds may be more sensitive to changes in nutrient concentrations, such as silica, than subarctic algae (Douglas, 1984). And many species of Bacillariophyceae, in particular, have been used as indicators of nutrient enrichment (van Dam et al. 1994, Stevenson et al. 2002), alkalinity (Rühland et al., 2003a; Rühland et al., 2003b) and pH (Rühland et al., 2003b). Given their importance as primary producers in both marine and freshwater environments (Smith et al., 2005; Winder et al., 2009), understanding the response of algae to environmental change is key to understanding global nutrient and energy cycles.

1.1 Objectives

1. Characterize the algal community composition in tundra ponds in Barrow, Alaska and determine the primary environmental factors structuring these communities.
2. Determine whether algal communities have changed over the past 40 years, by comparing current algal communities with data collected in 1972.

2. Methods

2.1 Study site

This study took place on the north slope of Alaska, near Barrow, AK. We focused on 2 regions, a historic study site called the International Biological Program (IBP) site, and a newly established study site the Barrow Environmental Observatory (BEO). Both sites are dominated by wet arctic tundra with many lakes and ponds of different sizes, and the region is underlain by continuous permafrost.

The International Biological Program (IBP) site was established in 1970 for environmental research focused on evaluating the responses of the tundra ecosystem to different artificial and natural disturbances (Miller et al., 1978). This area was intensively studied between 1971 and 1973 (Stanley, 1976). However, since that time, very little research has occurred in the IBP tundra ponds, and the village of Barrow has encroached on the IBP site, which raises some concerns that this valuable historic site could be affected by human disturbance.

The BEO covers 7,466 acres east of the village of Barrow and was founded in 1992 for two principal purposes. The first is to preserve the BEO in its natural condition and evaluate long-term year-round effects of climate change on Arctic tundra ecosystems. The second is to have long-term interactions and collaborations between national and international organizations, terrestrial, marine and atmospheric scientists and native people in research projects. Given their greater distance from the village of Barrow, these sites represent our "reference" sites and we hypothesized that these sites would more closely represent the conditions that may have been present in the IBP ponds in the 1970s.

We sampled four ponds in the BEO (WL20, WL14, BEAR, and CAT) and 5 ponds in the IBP (A, C, 10, E, B) (Figure 1). The IBP ponds were in close proximity to each other, with less than 250 meters separating each site. In fact, two of these ponds, A and B, were connected by a short, man-made channel. Conversely, the farthest distance between any 2 sites in the BEO was 1600 meters (Figure 1). All sites were visited between August 10-13 2008, except for Pond B, which was sampled on approximately the same date in August 2009. Furthermore, for a better understanding of seasonal fluctuations in algal communities, we sampled IBP pond B on a weekly to bi-weekly basis from June 18th to August 19th, 2010.

2.2 Field Methods

Sediment periphyton was collected from five separate locations in each pond using an inverted Petri dish and spatula. All five periphyton samples from the site were combined into one composite sample. Algae were separated from the sediment by vigorously mixing the sediment with distilled water and pouring off the surface liquid. This was repeated 10 times until the water was relatively clear, to get the final periphyton sample. The liquid sample was stored in a test tube and preserved with Lugol's iodine.

Environmental variables in each pond, such as nutrient levels (phosphorus, nitrogen), water conductivity, water temperature and soil organic matter, were measured in samples collected from open water as part of a different study (Lougheed et al. submitted).

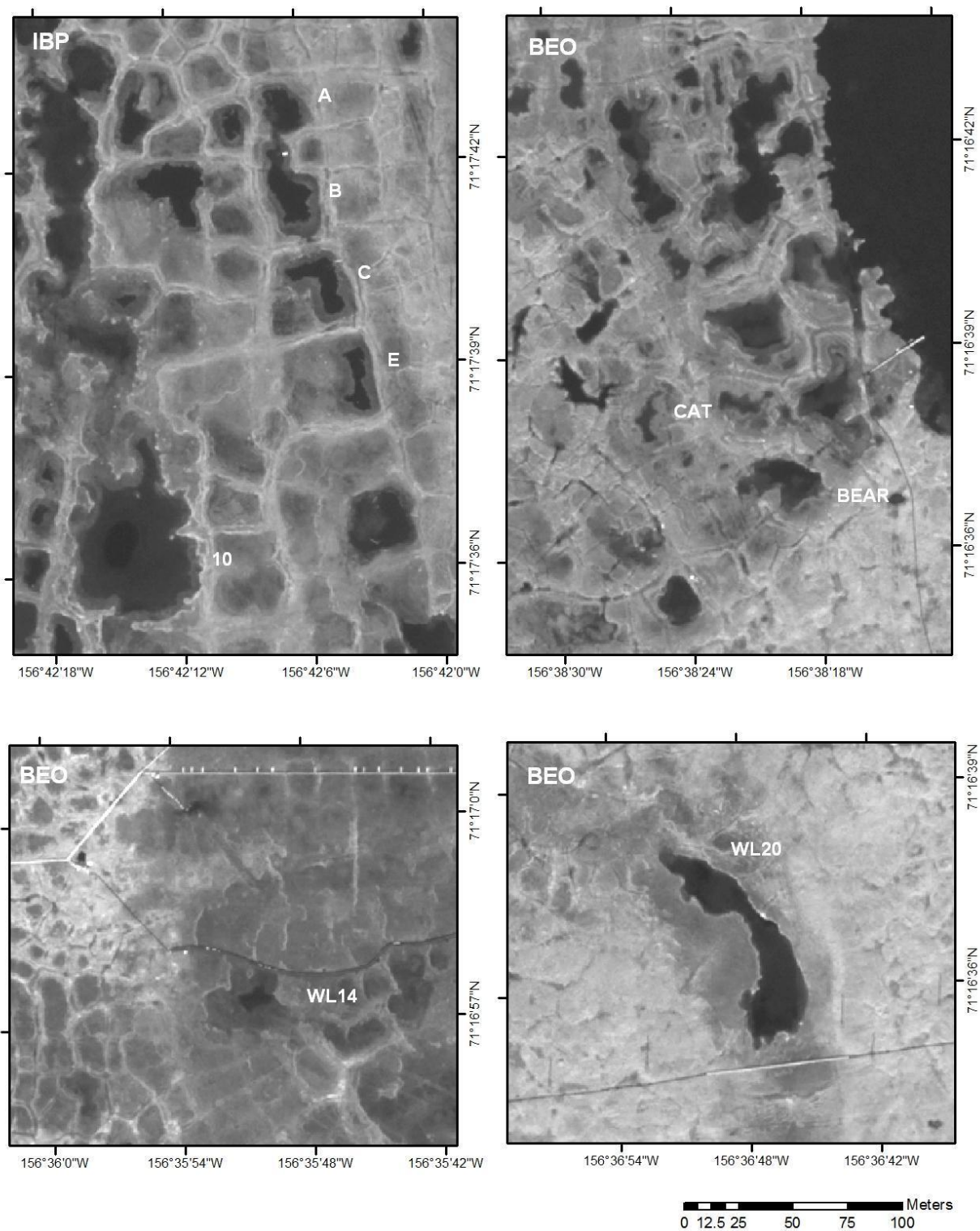


Figure 1. Satellite images showing the latitude and longitude of the 9 sampled ponds from IBP and BEO areas in Barrow Alaska.

2.3 Lab procedures

To determine the proportion of algal species in our samples, we added 1 ml of the preserved algae sample from each pond into a stainless steel Palmer counting cell, covered it with a cover slip, and observed it under a Zeiss Axioscope 40 light microscope. We found that 40X was the optimal magnification to clearly see and identify many algal taxa, but we also used the 100X magnification to confirm identification of smaller taxa. We counted and identified at least 300 algal cells per site. To ensure consistent identification of algal species, we took reference photographs, measured the dimensions (width and length) of each cell, and also took notes about main features of each taxa. For 2008-9 samples, taxa were identified to the lowest possible taxonomic unit, and also classified into broader taxonomic groups (Cyanophyta (blue-green algae), Chrysophyceae, Chlorophyta (green algae), Bacillariophyceae (diatoms), Cryptophyta and Euglenophyta). For the seasonal 2010 samples, taxa were identified to broad taxonomic groups only. For algal identification we used the following sources: Prescott and Scott, 1942; Prescott and Scott, 1945; Croasdale, 1957; Patrick and Freese, 1961; Patrick and Reimer, 1966; Prescott, 1978; Round et al., 1990; and, Wehr and Sheath 2003.

For identification of diatom species, we “washed” the diatoms in nitric acid to better observe the unique identifying structures. We put approximately 20 ml of the algae sample in a 225 ml Erlenmeyer flask and added an equivalent volume of nitric acid. The sample was boiled over medium heat on a hot plate in a fume hood until approximately half of the sample remained. The sample was repeatedly diluted with distilled water, left to settle, and then carefully decanted, making sure not to dispose of the diatoms that had settled at the bottom of the flask, until the sample had a pH of 7 (Rühland et al. 2003a ; Rühland et al. 2003b).

To calculate algal biomass, we used representative geometric formulas to estimate the biovolume based on the average cell dimensions of each algal taxa (Wetzel and Likens, 2000) and weighted this by the abundance of each group. For example, for ellipsoidal cells (e.g. *Cryptomonas*), we used the formula $\pi AB^2/6$ where A and B were length and width, respectively.

2.4 Statistical procedures

Sorensen's similarity index was calculated using EstimateS (Statistical Estimation of Species Richness and Shared Species from Samples, version 8.2.0) to find any similarities in species composition among all ponds and between ponds sampled in 2008, 2009 and 1972. Comparison among regions, including mean Sorensen's similarity index values and species richness, were completed using t-tests. To understand why ecological communities varied among sites and over the season, relationships between algal community structure and the measured environmental data and were determined using Pearson Correlation Coefficients. Data were log or arcsin transformed, as required, to meet the assumptions of normality. All statistical analyses were completed using SAS JMP (version 4).

3. Results

3.1 Species-level comparisons among sites and years

We counted 3,649 cells in total from 9 ponds in 2008-9. A total of 114 algal taxa were identified to species or genus level. This included 64 species of Bacillariophyceae, 29 species of Chlorophyta, 15 species of Cyanophyta, 2 species of Cryptophyta, 1 species of Chrysophyceae and 3 species of Euglenophyta. In addition, 2 % of all Chlorophyta, 4 % of all Cyanophyta, and 7 % of all Bacillariophyceae (by abundance) were unidentified small unicells. In 1972, Alexander listed 17 species of Chlorophyta, 1 species of Cryptophyta, 9 species of Cyanophyta and 12 species of Bacillariophyceae, of which 21 species were not found in 2008-9 samples (Table 1). The most common genera in 2008-9 were *Navicula*, *Eunotia*, *Neidium*, *Staurastrum*, *Stauroneis*, *Pinnularia*, and *Euastrum*, while the common genera in 1972 in pond B were *Microcystis*, *Aphanizomenon*, *Chlamydomonas*, *Closterium*, and *Ankistrodesmus* (Alexander et al., 1980).

Although this study focused on the periphyton, we did find that 9 species of phytoplankton found by Alexander et al. (1980) (*Chroococcus turgidus*, *Merismopedia glauca*, *Anabaena Laponica*, *Chlamydomonas frigida*, *Pediastrum boryanum*, *Scenedesmus armatus*, *Euglena viridis*, *Cryptomonas ovate* and *Cryptomonas* sp) were also found in our results for benthic algae in 2008-9. Three of these species (*Chroococcus turgidus*, *Chlamydomonas frigida* and *Cryptomonas* sp) were also observed in the 1972 benthic algal list. Alexander et al. (1980) also reported abundant Heterokonta in the periphyton for some experimental manipulations in Pond B; however, they did not list any species in this group. This issue made comparisons of these experimental data challenging. We suspect that they could be a constituent of a class Eustigmatophyceae (eg. *Chlorobotrys*) or class Xanthophyceae (eg. *Tribonema*); both were listed in 1972 phytoplankton species list, but not observed in this study (2008-9).

Table A. List of periphytic algae species found in 9 tundra ponds from Barrow Alaska in 2008-9 and from IBP pond B in 1972 (Alexander 1980).

Species name	BEO				IBP					1972
	WL14	WL20	CAT	BEAR	A	B	C	E	10	B
<u>Chlorophyta</u>										
<i>Ankistrodesmus falcatus</i>										x
<i>Ankistrodesmus spirale</i>										x
<i>Chaetosphaeridium</i> sp	x									
<i>Chlorococcum</i> sp	x					x		x	x	
<i>Closterium gracile</i>							x			x
<i>Closterium moniliferum</i>										x
<i>Chlamydomonas aciculare</i>										x
<i>Chlamydomonas frigida</i>										x
<i>Chlamydomonas lapponica</i>										x
<i>Chlamydomonas sessile</i>										x
<i>Closterium</i> sp	x		x	x	x	x	x	x	x	
<i>Closterium venus</i>				x				x		
<i>Cosmarium botrytis</i>				x						x
<i>Cosmarium granatum</i>				x						x
<i>Cosmarium ornatum</i>										x
<i>Cosmarium</i> sp	x	x	x	x	x	x	x	x	x	
<i>Elakatothrix lacustris</i>										x
<i>Euastrum ansatum</i>	x									
<i>Euastrum binale</i>	x				x					x
<i>Euastrum dubium</i>							x			
<i>Euastrum elegans</i>	x			x				x		x
<i>Euastrum</i> sp	x				x					
<i>Gleococcus schroeteri</i>										x
<i>Gonatozygon</i> sp					x					
<i>Penium margaritaceum</i>						x				
<i>Scenedesmus armatus</i>								x		
<i>Scenedesmus</i> sp								x		
<i>Sphaerellopsis</i> sp	x									
<i>Staurastrum armigerum</i>				x						
<i>Staurastrum claviferum</i>	x									
<i>Staurastrum cyrtocentrum</i>							x			
<i>Staurastrum gracile</i>										x
<i>Staurastrum luetkemuellerei</i>				x						
<i>Staurastrum punctulatum</i>								x		
<i>Staurastrum</i> sp			x	x	x	x		x	x	
<i>Staurastrum trihedrale</i>								x		
<i>Staurastrum turgescens</i>	x									
<i>Staurodemus teilingii</i>				x						
<i>Staurodesmus cuspidatus</i>						x				
<i>Staurodesmus mucronatus</i>						x				
<u>Chrysophyceae</u>										
<i>Dynobryon</i> sp							x			
<u>Cryptophyta</u>										
<i>Cryptomonas</i> sp								x	x	x
<i>Cryptomonas ovata</i>							x			

(Table A continued on next page)

Species name	WL14	WL20	CAT	BEAR	A	B	C	E	10	B
Cyanophyta										
<i>Anabaena lapponica</i>					x					x
<i>Aphanocapsa</i> sp							x			x
<i>Chroococcus turgidus</i>	x				x					x
<i>Cylindrospermum</i> sp	x									
<i>Eucapsis</i> sp	x									
<i>Gloeocapsa</i> sp	x					x				
<i>Gomphosoheria</i> sp										x
<i>Gomphospheria naegliana</i>										x
<i>Limnothrix redekei</i>	x									
<i>Merismopedia glauca</i>								x		
<i>Merismopedia</i> sp	x				x		x			
<i>Microcystis flos-aquae</i>										x
<i>Nostoc commune</i>						x				
<i>Oocystis lacustris</i>										x
<i>Oscillatoria agardii</i>										x
<i>Oscillatoria jenesis</i>							x			
<i>Oscillatoria</i> sp					x					x
<i>Pediastrum boryanum</i>	x				x	x		x		
<i>Spirulina</i> sp		x								
<i>Woronichinia naegeliana</i>	x									
Bacillariophyceae										
<i>Achnanthes flexella</i>			x	x	x	x				
<i>Amphipleura</i> sp							x	x	x	
<i>Amphora</i> sp							x	x		
<i>Aphanotheca clathrata</i>										x
<i>Aphanotheca</i> sp										x
<i>Aphanozomenon flos-aquae</i>										x
<i>Capartogramma</i> sp					x					
<i>Coelospherium kuetzingianum</i>										x
<i>Crucicula</i> sp						x				
<i>Cymbella laterostrata</i>	x			x	x					
<i>Cymbella minutum</i>						x				
<i>Cymbella</i> sp		x	x	x		x	x	x		x
<i>Encyonema elginense</i>					x					
<i>Encyonema minutum</i>					x					
<i>Encyonema</i> sp		x	x	x	x		x	x	x	
<i>Eunotia arcus</i>		x		x		x		x		
<i>Eunotia bidentula</i>		x	x							
<i>Eunotia curvata</i>					x					
<i>Eunotia elegans</i>			x	x	x	x	x	x	x	
<i>Eunotia glacialis</i>			x				x			
<i>Eunotia lunaris</i>										x
<i>Eunotia parallela</i>					x					
<i>Eunotia praerupta</i>		x		x	x	x		x	x	
<i>Eunotia</i> sp	x	x	x		x	x	x	x	x	x
<i>Fragilaria capucina</i>				x		x	x	x		
<i>Fragilaria Laponica</i>									x	
<i>Fragilaria</i> sp			x		x	x	x	x	x	x
<i>Gomphonema gracile</i>						x				
<i>Gomphonema</i> sp		x				x		x		
<i>Hannaea arcus</i>	x	x	x	x	x					

(Table A continued on next page)

Species name	WL14	WL20	CAT	BEAR	A	B	C	E	10	B
<i>Navicula bacillum</i>		x		x	x	x				
<i>Navicula lacustris</i>				x				x		
<i>Navicula laevisima</i>				x		x				
<i>Navicula pupula</i>		x		x	x	x	x	x	x	
<i>Navicula pupula var laevisima</i>			x							
<i>Navicula radiosa</i>					x					
<i>Navicula sp</i>		x	x	x	x	x	x	x	x	x
<i>Navicula vulpine</i>				x						
<i>Neidium affine</i>		x			x					
<i>Neidium affine var undulatum</i>				x				x		
<i>Neidium ampliatus</i>						x			x	
<i>Neidium hitchcockii</i>				x	x	x	x	x		
<i>Neidium iridis</i>	x		x	x	x	x	x	x		
<i>Neidium iridis var ampliatus</i>						x				
<i>Neidium iridis viridis</i>				x						
<i>Neidium temperei</i>	x			x		x		x		
<i>Nitzschia filiformis</i>			x				x			
<i>Nitzschia palea</i>							x			
<i>Pinnularia abaujensis</i>				x			x			
<i>Pinnularia abaujensis var rostrata</i>			x					x		
<i>Pinnularia legumen</i>				x						
<i>Pinnularia mesolepta</i>		x	x	x	x	x	x	x		x
<i>Pinnularia sp</i>	x	x		x	x	x	x	x	x	x
<i>Pinnularia viridis</i>							x			
<i>Satauroneis anceps</i>	x		x	x		x	x	x		
<i>Sellaphora bacillum</i>			x				x	x		
<i>Staurastrum claviferum</i>	x									
<i>Stauroneis anceps var anceps</i>					x		x			
<i>Stauroneis phoenicenteron</i>	x	x	x	x	x	x	x	x		
<i>Stauroneis phoenicenteron f gracilis</i>					x				x	
<i>Stauroneis phoenicenteron f phoenicenteron</i>									x	
<i>Stauroneis smithii</i>		x								
<i>Stauroneis sp</i>				x						x
<i>Stephanodiscus sp</i>	x									
<i>Surirella ovalis</i>					x					
<i>Synedra barrowiana</i>					x	x				
<i>Synedra incise</i>			x	x	x					
<i>Synedra sp</i>				x						
<i>Tabellaria flocculosa</i>		x	x	x		x	x			
<u>Euglenophyta</u>										
<i>Euglena viridis</i>	x					x				
<i>Trachelomonas kelloggii</i>			x							
<i>Trachelomonas sp</i>						x				

There were no significant differences in species richness among sites in the IBP and BEO regions (t-test, $p=0.2678$), with an average of 56 species found at the IBP sites and 48 species observed at the BEO sites (Figure 2). Conversely, there were only 38 species identified in 1972; 25 percent of these taxa were identified to genus level only. Similarly, in 2008-9 there was no difference in the Shannon-Wiener index among the IBP (3.58) and BEO (3.40) sites (t-test, $p=0.3739$, Figure 2).

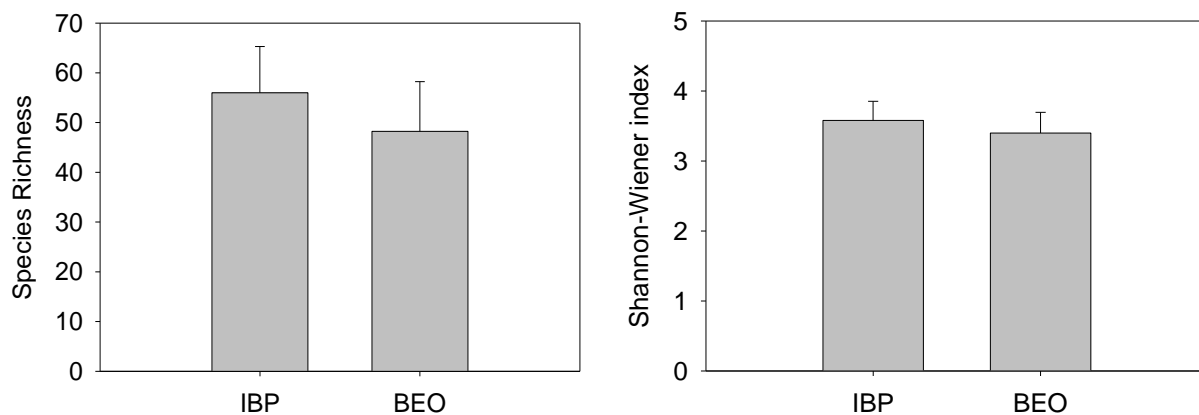


Figure 2. Average species richness (left) and Shannon-Wiener biodiversity index (right) of periphyton species in the IBP and BEO areas from Barrow, Alaska. Error bars represent 1 standard deviation.

On average, all ponds sampled in IBP and BEO areas during the 2008-2009 growing season had a relatively dissimilar species composition, with an average Sorensen's index of 0.18. BEO sites were more dissimilar to each other (Sorensen's Index = 0.3488 ± 0.1178) than the IBP ponds (Sorensen's Index = 0.4609 ± 0.0630) ($p = 0.0252$, $t = -2.505$, $n = 16$), which had approximately 50% similarity in species composition.

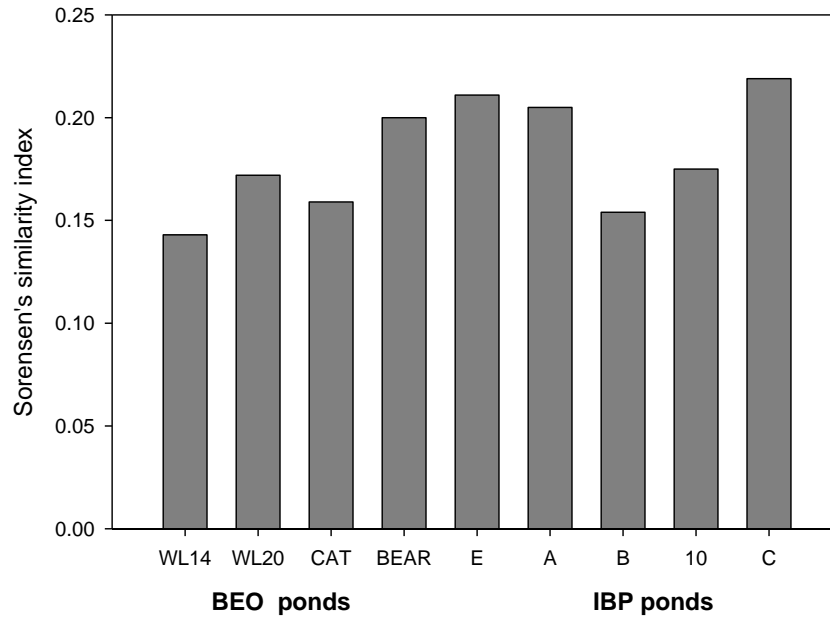


Figure 3. Average Sorensen's similarity index comparing all 9 ponds sampled in 2008-9 to IBP Pond B in 1972.

On average, these 9 ponds had a very dissimilar species composition as compared to IBP Pond B in 1972, with a mean Sorensen's index of 0.182. The highest similarity index was for Pond C (Sorensen's index = 0.219), indicating that Pond C 2008 and Pond B 1972 had 21% similar species composition, while Pond B 2008 had only 15% similar species with Pond B 1972 (Figure 3).

3.2 Group-level comparisons among sites and years

In all ponds in 2008-9, Bacillariophyceae showed the highest relative abundance; on average 80% of all algae counted in all ponds were represented by diatoms cells (Figure 4). The next most abundant taxonomic groups were the Cyanophyta and Chlorophyta. Similar results were obtained for relative biomass calculations; specifically, diatoms ranged from 99% of the relative algal biomass in pond WL20, to 72% of algal biomass in pond A. While Bacillariophyceae also represented the largest relative proportion of biomass in pond C at 42%, there was also relatively high biomass of Cyanophyta at 39% (Figure 5).

Conversely, periphyton biomass in IBP Pond B in mid-July, 1972 was dominated by Chlorophyta (50%), followed by Cyanophyta 45%, Bacillariophyceae 3%, Chrysophyceae 3 % (Figure 6).

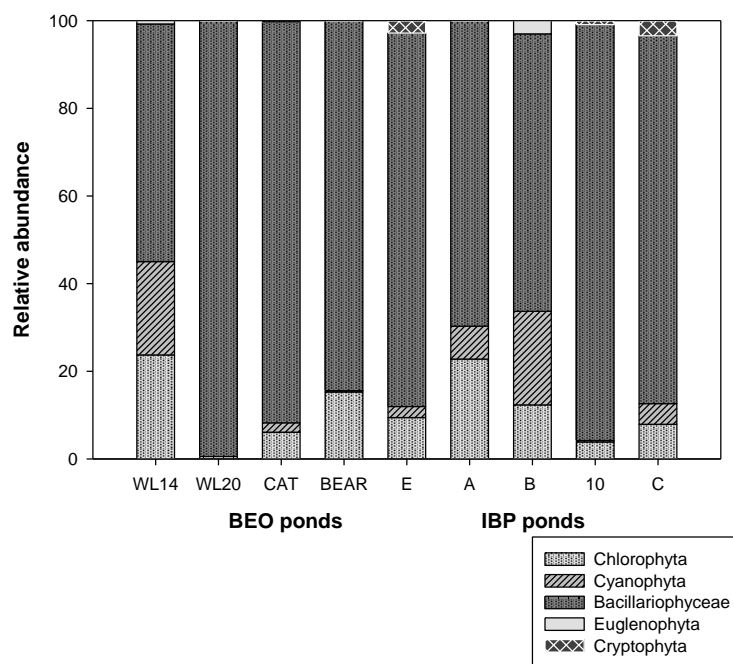


Figure 4. Relative abundance of algal groups in 9 ponds in the BEO and IBP regions of Barrow Alaska.

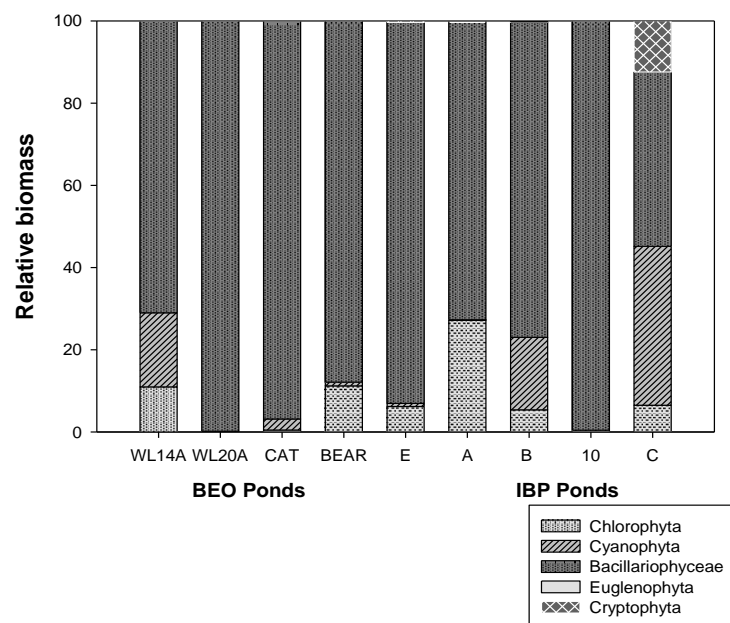


Figure 5. Relative biomass of algal groups in 9 ponds in the IBP and BEO areas from Barrow Alaska.

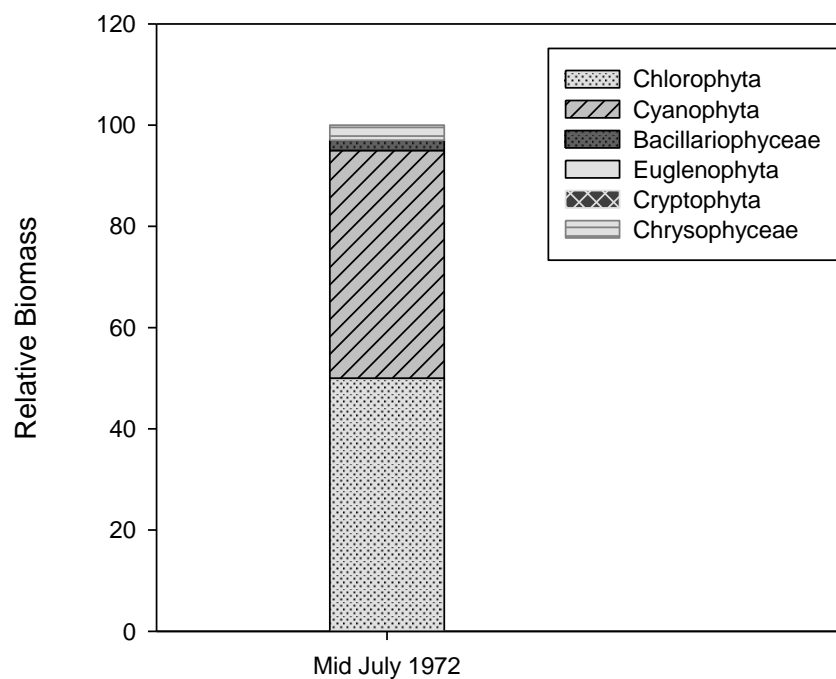


Figure 6. Relative algal biomass reported by Alexander (1980) for IBP pond B sampled in mid-July 1972.

Much like the species composition between IBP B in 1972 and the 9 sites visited in 2008-9 was very dissimilar (Table 1, Figure 2), broad taxonomic composition was also dissimilar. Mean Pearson's correlation co-efficients for taxonomic composition among all ponds sampled in 2008-2009 was high ($r = 0.91$) and 78% of all these correlations were significant. Conversely, taxonomic composition in IBP Pond B in 1972 was not significantly correlated to any of the ponds sampled in 2008-9 (average $r = -0.25$, $p > 0.05$).

3.3 Seasonal trends in Pond B, 2010

Analysis of periphyton samples from IBP Pond B over the 2010 growing season indicated that three algal groups dominated algal abundances: the Chlorophyta, Cyanophyta and Bacillariophyceae. Similar trends were observed in relative biomass, where we saw a predominance of Cyanophyta at the beginning of the growing season, followed by fluctuations in dominance near the end of the season by Cyanophyta and Bacillariophyceae. We also observed a relatively small contribution of Chlorophyta, Euglenophyta, Cryptophyta and Chrysophyceae to algal biomass and abundance during the growing season (Figure 6). We counted a total of 2266 algal cells represented by 43.8% of Cyanophyta, 41.96% of Bacillariophyceae, 13% of Chlorophyta, 0.57% of Euglenophyta, 0.44% Chrysophyceae, and 0.13 % of Cryptophyta.

Mean Pearson's correlation co-efficients indicated that the date where composition was most highly correlated among IBP Pond B in 1972 and IBP Pond B sampled throughout 2010 was the week of July 9th, 2010 ($r = 0.8141$, $p=0.0935$).

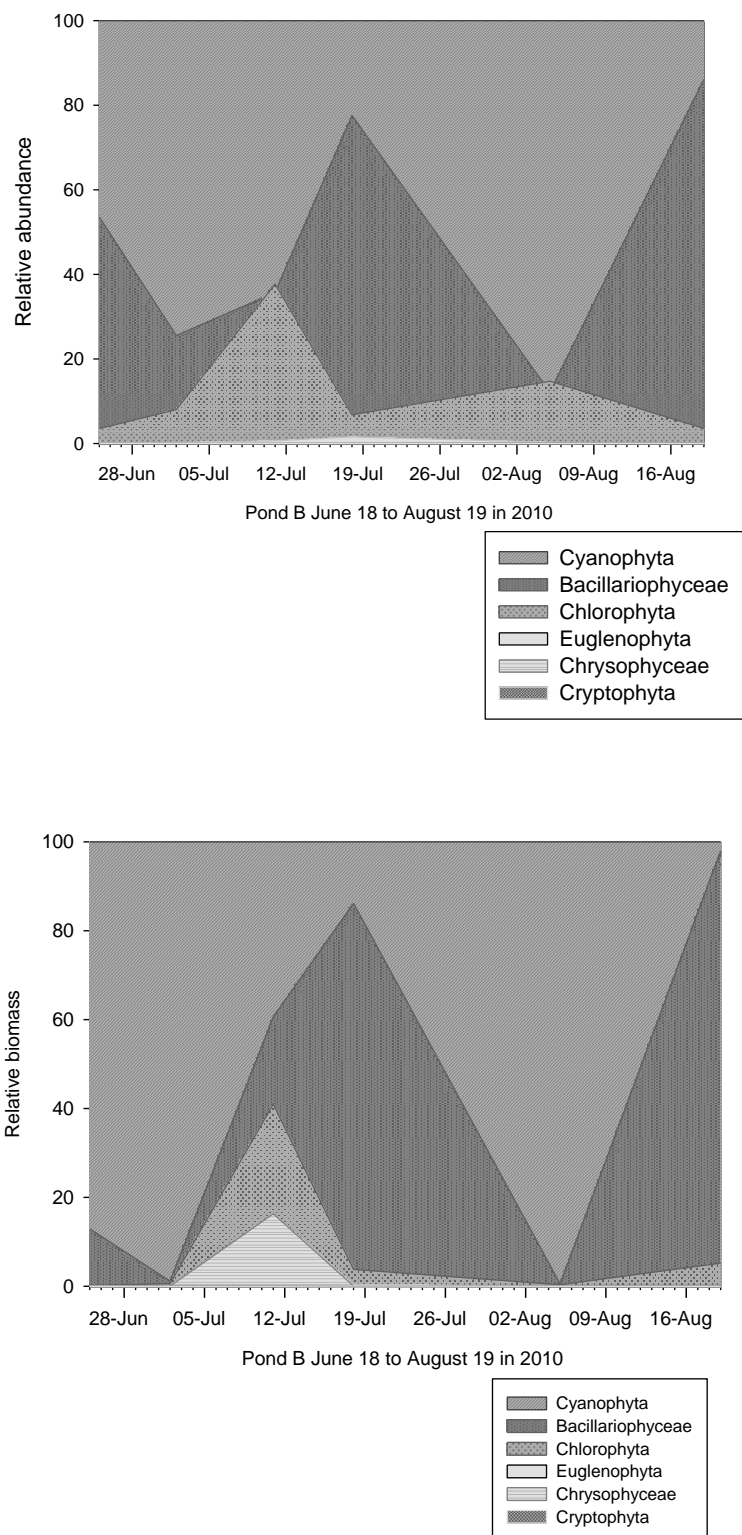


Figure 8. Relative abundance (top) and relative biomass (bottom) of different algal groups in IBP Pond B during the growing season of 2010.

3.4 Environmental determinants of algal community composition

An examination of the environmental factors driving algal biomass and abundance in the 9 ponds in the IBP and BEO in 2008-10 was performed using correlation analysis. Two of the strongest correlations were the negative correlations between Cyanophyta and Bacillariophyceae algal abundance ($r = -0.79$, $p < 0.05$, Table D) and biomass ($r = -0.87$, $p < 0.05$, Table B), indicating that as the Bacillariophyceae increased in proportion, Cyanophyta declined. Bacillariophyceae and Cyanophyta also tended to have opposing relationships with nutrient concentrations and conductivity. Cyanophyta relative biomass declined with increasing water column conductivity ($r = -0.69$, $p < 0.05$, Table C) and phosphorus ($r = -0.59$, $p < 0.05$, Table C), while Bacillariophyceae relative biomass and abundance increased with both water column conductivity ($r = 0.61-0.72$, $p < 0.05$, Tables C and E) and nitrates ($r = 0.63-0.67$, $p < 0.05$, Tables C and E). Cyanophyta relative abundance also declined with increasing levels of sediment total organic carbon ($r = -0.83$, $p < 0.05$, Table E), but increased with temperature ($r = 0.64$, $p < 0.05$, Table E).

Chlorophyta relative abundance also tended to be negatively correlated with the Bacillariophyceae ($r = -0.54$, $p < 0.05$, Table E); however, no strong correlations were found between the Chlorophyta and environmental variables. The only other strong correlations ($p < 0.05$), were a negative correlation between Euglenophyta relative abundance and sediment total organic carbon ($r = -0.96$, $p < 0.05$, Table E), and a negative correlation between Chrysophyceae relative abundance and ammonia concentrations ($r = -0.84$, $p < 0.05$, Table E).

Table B. Correlation analysis between relative biomass of algal groups from 2008, 2009 and 2010 in all 9 tundra ponds (**p<0.05, *p<0.10).

Variable	Chlorophyta	Cryptophyta	Cyanophyta	Bacillariophyceae	Euglenophyta
Cryptophyta	0.58				
Cyanophyta	-0.35	0.93*			
Bacillariophyceae	-0.13	-0.88	-0.87**		
Euglenophyta	-0.12	0.00	-0.49	0.47	
Chrysophyceae	-0.10	-0.09	0.58 **	-0.40*	-0.06

Table C. Correlation analysis between relative biomass of algal groups and environmental variables for 2008, 2009 and 2010 data (**p<0.05, *p<0.10). The number of correlations possible, based on the availability of environmental data, is indicated by "n".

Variable	Conductivity n=17	Ammonia (NH ₃) n=8	Nitrate (NO ₃ -N) n=15	Sediment Total Phosphorus n=9	Total Phosphorus n=14
Chlorophyta	0.10	-0.72	-0.09	0.65*	0.32
Cryptophyta	0.24	0.00	-0.08	-0.49	-0.66
Cyanophyta	-0.69**	-0.23	-0.52*	-0.10	-0.59**
Bacillariophyceae	0.72**	0.66	0.67**	-0.31	0.47
Euglenophyta	0.06	0.63	-0.03		0.41
Chrysophyceae					

Table D. Correlation analysis between relative abundance of algal groups from 9 ponds sampled in 2008, 2009 and 2010 (**p<0.05, *p<0.10).

Variable	Chlorophyta	Cryptophyta	Cyanophyta	Bacillariophyceae	Euglenophyta
Cryptophyta	0.58				
Cyanophyta	0.21	-0.21			
Bacillariophyceae	-0.54**	-0.16	-0.79**		
Euglenophyta	0.17	-0.17	0.15	-0.23	
Chrysophyceae	-0.09	-0.08	0.58**	-0.39	-0.06

Table E. Correlation analysis between relative abundance of algal groups and environmental variables measured in 9 tundra ponds over 2008, 2009 and 2010 (**p<0.05, *p<0.10). The number of correlations possible, based on the availability of environmental data, is indicated by "n".

Variable	Conductivity n=15	Ammonia (NH ₃) n=7	Nitrate n=7	Sediment Total Organic Carbon (g/kg) n=8	Sediment Total Phosphorous (mg/g) n=8	Total Phosphorus n=13	Temperature n=16
Chrysophyceae	-0.32	-0.84**	-0.15			0.09	0.18
Cyanophyta	-0.41	-0.52	-0.22	-0.83**	0.40	0.08	0.64**
Chlorophyta	-0.12	-0.05	-0.34	-0.53	0.68*	-0.55*	0.05
Cryptophyta	-0.52**	-0.17	-0.52*	0.40	-0.11	-0.25	-0.32
Bacillariophyceae	0.61**	0.69	0.63**	0.60	-0.53	0.26	-0.42
Euglenophyta	-0.05	0.33	-0.25	-0.96**	-0.01	0.02	-0.13

Finally, a regression plot of relative biomass of taxonomic groups of all 9 sites sampled in 2008, 2009 and 2010 indicates an opposite behavior between Bacillariophyceae and Cyanophyta (Figure 7). Bacillariophyceae relative abundance tends to increase as the summer progresses and Cyanophyta declines. When data from 1972 is overlain on this graph, the plotted data points (triangles) lie near to the regression lines through relative biomass data from 2008-10.

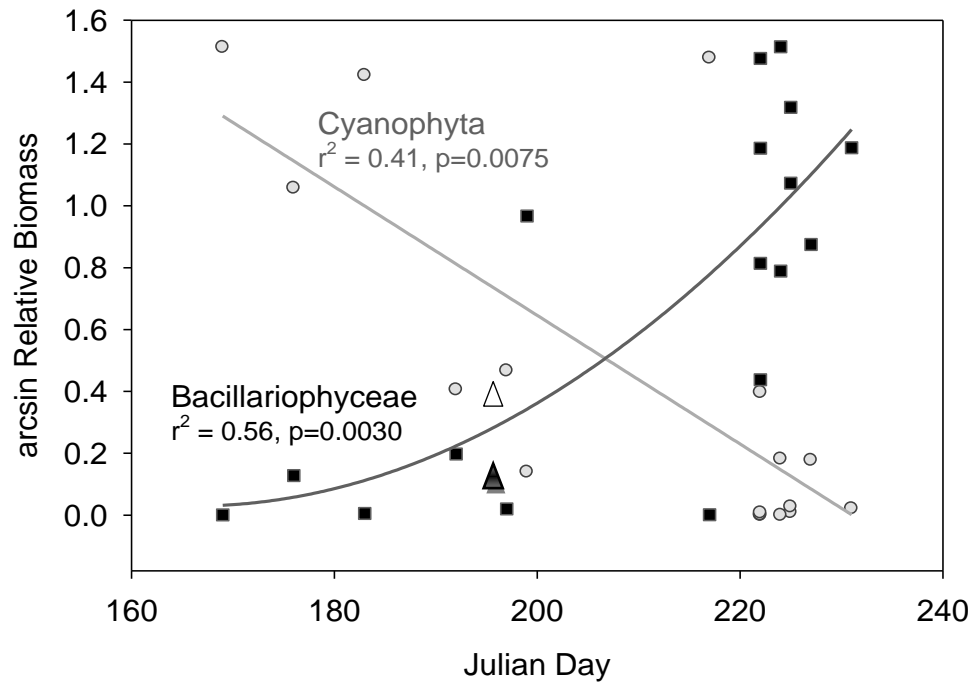


Figure 7. Regression analysis of Cyanophyta and Bacillariophyceae relative biomass against Julian days in 2008-10. Triangles indicate the 1972 data (black represent Bacillariophyceae and white represent Cyanophyta).

4. Discussion

This study took advantage of an invaluable historic dataset on algal community structure to describe large changes in algal species composition in Arctic tundra ponds over the last 40 years. Gross changes in taxonomic conditions were correlated with nutrient concentrations and indicated potential competition among algal groups for nutrients.

The Sorensen's similarity index indicated that algal communities in the IBP ponds were more similar to each other than those in BEO ponds. This characteristic can be a consequence of the distance between ponds in these 2 regions. The more taxonomically similar IBP ponds were separated by a distance less than 250 meters, while the BEO ponds had the farthest distance between two sites of 1600 meters. At the IBP ponds, water flows between the ponds for a few days each spring during snow melt (Hobbie, 1980). The greater proximity of the IBP ponds to each other may thus contribute to a greater ease of dispersal among ponds and greater similarity among algal communities (Cohen and Shurin, 2003). Biota may also become more similar among sites with nutrient enrichment and homogenization of aquatic habitats (Lougheed et al. 2008). However, preliminary data has indicated that the BEO and IBP ponds do not have significantly different nutrient concentrations (Lougheed, unpubl. data).

We observed very little similarity in taxonomic composition between tundra ponds sampled in August 2008 and 2009 and species lists from IBP Pond B 1972. On a broad taxonomic level, we found species belonging to Chlorophyta, Cryptophyta, Cyanophyta, Chrysophyceae, Euglenophyta and Bacillariophyceae in 2008-9, while Alexander et al. (1980) recorded no species of Cryptophyta or Euglenophyta in 1972. In addition, in mid-July 1972 Chlorophyta and Cyanophyta made up more than 90% of the total biomass in pond B 1972 (Alexander et al., 1980), but on the contrary in 2008-9 we noticed that Bacillariophyceae made up on average an 80% of biomass in all ponds.

Species composition was also very dissimilar between the 2 time periods, with an average Sorensen similarity co-efficient of only 0.18. Alexander et al. (1980) listed only 38 species of benthic algae, while we found an average of 48 species at the IBP ponds. Two-thirds of the common genera observed in 1972 were completely absent in 2008-9. Our initial hypothesis that the sites sampled in 1972 would have a more similar species composition to the more isolated sites at the BEO was not supported, as we found that all BEO sampled sites had a low similarity (less than 0.20) compared to IBP Pond B in 1972. As mentioned previously, the IBP and BEO ponds do not generally differ in nutrient concentrations (Lougheed et al., submitted). These comparisons could suggest that environmental conditions are changing in these Arctic tundra ponds; however, since sampling in these 2 time periods occurred in different months (July in 1972 versus August in 2008-9), more detailed seasonal comparisons were completed.

Changes in algal community composition through time could be attributed in part to warmer conditions in arctic ponds. In the 19th century, scientists using paleolimnological techniques observed the replacement of a dominant benthic genera *Fragilaria* by diverse taxa such as *Achnanthes*, *Caloneis*, *Cymbella*, *Navicula*, *Nitzschia*, and *Kraskella* in high arctic ponds (Douglas et al., 1994), that was likely related to climate warming. Similarly, in 2008-9 we observed some of these same taxa for the first time, including *Achnanthes flexella* and 2 species of *Nitzschia*, and also observed more species of the other genera, including more than 3 new species of *Cymbella*, 7 new species of *Navicula*, and 3 new species of *Fragilaria*.

While our species-levels changes are similar to those seen in other arctic ponds, comparisons to other studies indicate that ponds and lakes have unique algal communities. For example, some authors have reported the replacement of different diatom genera such as *Fragilaria*, *Achnanthes*, and *Aulacoseira*,

by more planktonic genera such as *Cyclotella* with warming and stratification of arctic and subarctic lakes (Sorvari et al., 2002; Rühland et al., 2003a; Smol et al., 2005; Winder et al., 2009). We did not, however, observe similar trends and, in fact, *Cyclotella* and *Aulocoseira* were never observed in the tundra ponds in Barrow. Our study sites are quite different from those lakes listed above, since ponds are smaller, have short periods of open water and don't tend to stratify. Although tundra ponds appear different from lakes, we did find several of the phytoplankton species reported by some authors (Sheath, 1986) in Barrow periphyton communities. This is likely caused by the relatively shallow depth of the ponds, which put phytoplankton in close contact with the sediment, as well as continuous water movements by winds that are conducive to phytoplankton and periphyton aggregation, removal and dispersal (Sheath, 1986).

While we found large changes in species composition through time and broad dissimilarity between 1972 relative biomass and those observed in 9 ponds throughout the Barrow area in 2008, seasonal patterns indicated that the relative biomass of the different algal groups in Pond B in late-July to mid-August 2010 was similar to that observed in the same pond in 1972. Similarly, Douglas et al. (1984) found drastic changes in Bacillariophyceae algal composition over the time, but no changes in the relative abundance of this group.

Paleolimnological evidence of diatom community change in the Arctic in the 19th century has been linked to climate warming (e.g. Douglas et al. 1994; Sorvari et al., 2002); however, these previous studies are limited in that they do not have access to concurrent measurements of associated environmental variables to understand how other factors may structure algal communities. Furthermore, these studies focus on diatoms (Bacillariophyceae), whose cell walls are made up mainly of silica and can be preserved in sediments for long periods of time; however, other taxonomic groups are ignored.

This study provides the first opportunity to link community change of multiple groups of algae on a decadal time scale with changes in nutrient concentrations in arctic tundra ponds.

Early in the growing season 2010, algae in IBP Pond B was dominated by Cyanophyta and then fluctuated throughout the later part of the growing season to Bacillariophyceae dominance later in the season, with a minor contribution of Chlorophyta. Interestingly, when Bacillariophyceae dominated the ponds, other algal groups such as Cyanophyta and Chlorophyta decreased dramatically in relative abundance and/or biomass, suggesting an exclusion of other groups when Bacillariophyceae dominated. Conversely, when Cyanophyta dominated, other algal groups such as Cryptophyta and Chrysophyceae increased in abundance. These two main taxonomic groups, Cyanophyta and Bacillariophyceae, maintained this strong negative correlation throughout the growing season, which raised the interesting question: what was controlling or contributing to these fluctuations?

Preliminary results from a different project indicate that DOC (dissolved organic carbon) increases significantly in the tundra ponds over the growing season. Some authors have indicated that DOC may protect algae from the harmful effects of UV radiation and also impact diatom species abundances (Antoniades et al., 2005), while Cyanophyta dominate under high levels of radiation (Vincent, 2002). The increase in DOC over the season may have reduced light penetration and incoming radiation, thus leading to the dramatic shift to Bacillariophyceae dominance in our arctic ponds as they gained the competitive advantage.

Both relative abundance and biomass of Bacillariophyceae was significantly positively correlated with nitrate concentrations and water column conductivity. Conversely, Cyanophyta abundance declined with water column conductivity and total phosphorus, and had a marginally significant negative correlation

with nitrate. Cyanobacteria have often been shown to dominate under low nutrient conditions (Van der Grinten et al., 2004), particularly in the Arctic (Vezina and Vincent, 1997) and under conditions of nitrogen limitation (Paerl et al., 2000, Skamoto and Bryant, 1998). Some Cyanophyta have developed mechanisms to fix atmospheric nitrogen and the ability to migrate vertically to find nutrients (Paerl, 2000). Furthermore, other authors have shown that Cyanobacteria often dominate polar ecosystems (Sheath and Cole, 1992,) because they are tolerant of prevailing conditions, including tolerance to freezing, broad temperature ranges and high levels of radiation (Tang 1997, Vincent, 2002).

In this study, Cyanophyta were the major component of algal biomass in 1972, when nitrate and phosphorus levels were significantly lower than they are today (Lougheed et al. submitted). The replacement of Cyanophyta by diatoms may have occurred due to this increase in nutrient availability, which increased the competitive advantage of diatoms. Similarly, Hernandez (unpubl. data) recently completed a preliminary study that indicated that algae in the IBP ponds have become nitrogen limited, especially later in the season when diatoms dominate, whereas they were phosphorus limited in the 1970s (Alexander 1980). This preliminary study may help to explain change in algal biomass through time; however, more research is required.

Organic sediments dominate the tundra ponds which, are underlain by permafrost soils. In the 1970s, organic matter concentrations in IBP pond sediments exceeded 70%, on average, and tundra ponds near the edge of drained lake basins had lower organic matter in the sediments compared to centrally located sites (Prentki et al. 1980). In 2008-09, relative abundance of Cyanophyta and Euglenophyta was negative correlated with sediment organic matter and the three sites with the lowest sediment TOC (WL14, CAT, BEAR) were not centrally located in drained lake basins. The effect of this increased organic matter on algal communities may be related to the increased availability of nutrients in organic

sediments; however more research is needed in this area, especially considering the rarity of Euglenophyta algal cells in our samples.

Many algal species can be bioindicators pointing to the presence of some specific environmental characteristics. In 2008-9, we found a relatively high proportion of Bacillariophyceae, several of which may be used as indicators of nutrient enrichment (Van Dam et al., 1994, Stevenson et al., 2002), including *Nitzschia palea* (Trobajo et al., 2009, Branco et al., 2010), *N. filiformis* (Gomez and Licursi, 2001) and *Euglena viridis* (Panich-pat et al., 2009). While only a few cells of each of these species was counted, these taxa could be an important parameter to monitor continuously in the future to track if any further changes in nutrient enrichment occur. In particular, the encroachment of the village of Barrow to the IBP ponds, and the maintenance of a road leading to the local landfill near ponds BEAR and CAT, could be future potential concerns.

To further understand these trends, future research directions could include:

- An experiment to evaluate the relative proportion of algae groups that grow on different nutrient diffusing substrates, or under different levels of shading, could help determine the role of nutrients on algal taxonomic composition.
- In addition, Alexander (1980) suggested that blue-green algae were responsible for fixing large amounts of nitrogen in the tundra ponds. Future experiments could be designed to following movement of nitrogen isotopes through the food web.
- As a consequence of our finding of nutrient pollution indicator species, we suggest more sampling to search for these pollution indicators in Barrow ponds.
- There is also the necessity to perform algal species counts in mid-July to evaluate if some of the species found in 1972, but absent in 2008-9, were observed at different times of the year.

- Other interesting organisms to explore in the IBP ponds are the phytoplankton because more detailed information exists for phytoplankton in the 1970s and thus, more detailed seasonal and taxonomic comparisons could be made.
- Finally, there is also abundant information on zooplankton abundances and fecundity in the IBP ponds during the 1970sa. Any changes in zooplankton abundances or fecundity over the past 40 years may also reflect a repercussion of changes in primary production, algal composition and environmental changes.

5. Conclusion

In conclusion, our data showed that algal species composition is not the same as it was 38 years ago, and we suggest that changes in algal biomass and abundance are likely related to changes in nutrient concentrations related to permafrost thaw and the nutrient limitation of specific algal groups. Conversely, gross taxonomic composition in mid-summer was similar between 2010 and 1972. The dominant algal groups in 2008-10 were Cyanophyta and Bacillariophyceae. Cyanophyta tended to dominate under either low nutrient, high light conditions, whereas, Bacillariophyceae dominated when nutrient levels were highest. We found algal bioindicator taxa at some sites but they were rather low in relative abundance; however, we recommend paying attention to these species because they are important pollution indicators. While we have obtained some ideas about what is happening to lower trophic levels in arctic ponds near to Barrow Alaska, more research is required to identify exactly the environmental and biological factors that are responsible for those changes.

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Vita

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