Changes in Tundra Pond Limnology: Re-sampling Alaskan Ponds After 40 Years

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Abstract The arctic tundra ponds at the International Biological Program (IBP) site in Barrow, AK, were studied extensively in the 1970s; however, very little aquatic research has been conducted there for over three decades. Due to the rapid climate changes already occurring in northern Alaska, identifying any changes in the ponds' structure and function over the past 30–40 years can help identify any potential climate-related impacts. Current research on the IBP ponds has revealed significant changes in the physical, chemical, and biological characteristics of these ponds over time. These changes include increased water temperatures, increased water column nutrient concentrations, the presence of at least one new chironomid species, and increased macrophyte cover. However, we have also observed significant annual variation in many measured variables and caution that this variation must be taken into account when attempting to make statements about longer-term change. The Barrow IBP tundra ponds represent one of the very few locations in the Arctic where long-term data are available on freshwater ecosystem structure and function. Continued monitoring and protection of these invaluable sites is required to help understand the implications of climate change on freshwater ecosystems in the Arctic.

Keywords Arctic tundra ponds · Climate change · Nutrients · Algae · Plant communities · Species change · Temperature

INTRODUCTION

The Arctic region is experiencing a period of unprecedented warming (Callaghan et al. 2004), and tremendous changes have been recorded in Arctic freshwater

ecosystems in response to global climate change. In the paleolimnological record, Smol et al. (2005) and Douglas et al. (1994) observed dramatic changes in diatom communities in high Arctic lakes and ponds over the past 150 years. Decreased ice cover, due to environmental warming, has resulted in longer growing seasons for algae and other organisms, and has been linked to increased primary production and changes in algal and invertebrate communities (Smol et al. 2005; Keatley et al. 2008). Spectral reflectance measurements on sediment cores also suggest that climate warming over the past 150 years has led to increased primary production in Arctic lakes (Michelutti et al. 2005). Evidence from several locations suggests that warming permafrost may be releasing nutrients and dissolved organic carbon (DOC) into Arctic freshwater ecosystems (Hobbie et al. 1999; Frey and Smith 2005; Schindler and Smol 2006). Despite these compelling trends, there is generally a scarcity of long-term data sets in the Arctic, especially in freshwater ecosystems (Smol and Douglas 2007b), and the effects of warming and permafrost thaw on Arctic freshwater ecosystems remain poorly understood.

The village of Barrow, AK, is the northernmost settlement in the United States (Fig. 1) and has been home to an active scientific research program since the 1940s. The region is underlain by continuous permafrost, with a maximum seasonal thaw (active layer) depth ranging from 30 to 90 cm in thickness (Hinkel and Nelson 2003). The coastal plain of the Alaskan North Slope has changed substantially over the past 40 years. Temperature and length of growing season have increased (Callaghan et al. 2004). Ponds in the region appear to have greater plant cover than recorded during in the 1970s (Stow et al. 2004). While there have been no reported losses of lakes and ponds on the Arctic coastal plain (Riordan et al. 2006),

water bodies in areas of discontinuous permafrost are declining in area and abundance (Smith et al. 2005; Rierdan et al. 2006). Furthermore, the human population, and its consequent anthropogenic sources of pollutants, has been steadily increasing in the region, and nutrient and chemical pollution in Arctic ecosystems, from both local and distant sources, is an emerging concern (Schindler and Smol 2006).

Despite the fact that about 22% of the land area on the Arctic Coastal Plain is covered with lakes, and more than 65% is marked by former lake basins filled with ponds (Hinkel et al. 2003; Frohn et al. 2005), relatively little limnological research has been conducted at Barrow since the late 1970s. During the 1970s, however, there was a substantial emphasis on limnology in the Barrow area and research performed at that time was paramount in pioneering arctic limnology and arctic ecological research in general. In 1971, the US National Science Foundation (NSF) funded the International Biological Program (IBP)—Tundra Biome project near the village of Barrow. The aquatic portion of that project culminated in a volume titled “The Limnology of Tundra Ponds” (Hobbie 1980). This report summarized the numerous publications of many scientists who cooperated to understand the ecology of ponds and a few lakes near Barrow, with a focus on energy flow and factors controlling productivity. With their intensive historical data, the IBP ponds represent a valuable, and virtually untapped, resource for studying ecological change on a decadal time scale.

The IBP ponds are small (30 × 40 m), shallow (<0.5 m deep) ponds occupying low-centered ice wedge polygons and surrounded by wet tundra within a large thaw-lake basin. Water flows between the ponds for only a few days each spring during snow melt, with no above- or below-ground flow for the rest of the summer, except in the rare event of exceptionally heavy rains. During the summer, most water lost from the ponds through evaporation is balanced by precipitation. During the IBP project, several ponds in the center of a former lake basin were studied on a regular basis, while additional ponds were visited or manipulated on occasion (Hobbie 1980) (Fig. 2). Researchers in the 1970s found that both planktonic and benthic algae in the IBP tundra ponds had temperature optima that were higher than ambient temperatures, indicating their potential to increase growth rates under warmer conditions (Stanley and Daley 1976; Alexander et al. 1980). Researchers also found that pond algal growth and photosynthesis were limited by phosphorus. When phosphorus was added to the ponds, nitrogen became limiting and enhanced the growth of nitrogen-fixing blue-green algae in the sediment (Alexander et al. 1980). Phytoplankton biomass and primary production were also controlled by zooplankton grazing, while benthic algae were likely kept low by bioturbation of animals (Alexander et al. 1980). The consumers in these ponds were primarily cladocerans, copepods, and anostracans in the water column (Stross et al. 1980), and a diverse assemblage of chironomid larvae in the sediments (Butler et al. 1980).

Fig. 1 Location of IBP tundra ponds site near Barrow, Alaska (71.29N, 156.79W)

Fig. 2 IBP tundra ponds in Barrow, Alaska. *Numbers* and *letters* correspond to sites names assigned to the ponds in the 1970s; several of these ponds were re-visited in this study

Recently, air temperatures in the Barrow region have increased by 0.7°C per decade (Hobbie et al. 1999), and this has likely led to increased water temperatures. However, establishing a direct relationship between air and water temperatures is complicated by wind, depth, ice cover, and other physical processes that determine water temperatures in water bodies (Livingstone and Lotter 1998; Livingstone and Dokulil 2001). Warmer temperatures may impact arctic ponds through a variety of factors, including reduced pond area (Smol and Douglas 2007a), increased primary production (Michelutti et al. 2005), and increased nutrient and DOC levels (Hobbie et al. 1999, Schindler and Smol 2006). The IBP pond studies from the 1970s provide a baseline of temperature data, against which more recently acquired data can be compared. Despite a large data gap between the IBP study of the early 1970s, and more recent data collected in the twenty-first century, these data

represent a valuable starting point for examining changes in freshwater temperatures in the Arctic.

This article represents one of the first analyses of the physical, chemical, and biological characteristics of the Barrow IBP tundra ponds since the 1970s. Given the prevalence of tundra ponds on the Arctic landscape, documenting their response to warming is important to understanding regional carbon and energy balance, energy flow, and biodiversity. The IBP ponds and their historic data represent a valuable and untapped resource for studying the impact of global change on aquatic environments at northern latitudes.

The goals of this study are to present an initial look at how the physical, chemical, and biological characteristics of the Barrow IBP tundra ponds have changed since the 1970s. In particular, we present data on water temperature, changes in nutrient chemistry, phytoplankton biomass, and

some initial observations of macroinvertebrate community change.

MATERIALS AND METHODS

Water Temperature

Water temperatures were monitored in IBP Pond C during 1971, 1972, and 1973, from shortly after pond thaw through the third week of August each year. A telethermometer placed on the pond sediment at approximately 20–30 cm water depth recorded sediment-surface temperatures hourly on a potentiometric recorder (Stanley 1974). During 2007, 2008, and 2009, Hobo Pro[®] waterproof temperature loggers collected hourly temperatures from the same location in Pond C, year-round beginning on 13 June 2007. Daily temperature averages, maxima, and standard deviations were summarized into weekly averages for each year, which were then sorted and averaged by “early” years (i.e., 1971–1973) and “late” years (i.e., 2007–2009). We present only data from weeks for which there were paired data for both the early- and late-years, which was the 11-week period beginning in week 25 of the year and extending through week 35, roughly corresponding to mid-June through mid-August.

In order to test for differences in the pond’s temperatures in the 1971–1973 versus 2007–2009, we regressed the weekly response variables for the late years versus those of the early years, using as a null hypothesis both an intercept equal to zero and a slope equal to unity. We also generated time-series graphs of these data and fit a second-order polynomial line through the temperature by week data to account for the seasonal amplitude of temperatures during the season in order to visualize seasonal differences between the early and the late years. We used an *F* test for equality of variance between residuals from the polynomial model, and residuals from a null model that the best estimate for temperatures was the simple average over the ice-free season. This test is analogous to the *F* statistic generated automatically by software packages as output for a linear regression. We did the calculations manually since we used a piece-wise nonlinear function (i.e., polynomial trends were fit separately to the EARLY and LATE periods) to model temperature against time.

Water Chemistry and Algal Biomass

While many nutrient chemistry and algal data were collected from the IBP tundra ponds in the early 1970s, for the purposes of this study we are comparing 3 years of data

collected from IBP Ponds B, C, and E (Fig. 2) during the months of August 1970, 1971, and 1972, to 3 years of data collected from the same ponds in August 2008, 2009, and 2010. During the 1970s, a total of 9–12 samples were collected per pond, while between 6 and 7 samples were collected per pond in 2008–2010.

Nutrient chemistry of water was analyzed using standard methods (American Public Health Association 1998) that best reflected methods utilized during the IBP (Hobbie 1980). Nitrate-nitrogen was determined by cadmium reduction; ammonia by the phenate method; total phosphorus by ascorbic acid method following persulfate digestion; soluble reactive phosphorus by the ascorbic acid method; and, silica by the heteropoly blue method. Phytoplankton chlorophyll *a* was measured after extraction in 90% acetone and concentrations estimated according to Strickland and Parsons (1972). Concentrations were compared using a *t* test, with data log-transformed to meet the assumption of normality.

Macroinvertebrates

Macroinvertebrate studies during the IBP years lacked taxonomic resolution, but more intensive work on benthos in these same ponds was conducted in 1975–1977 (Butler 1980a, b, 1982a, b; Butler et al. 1980). Butler et al. (1980) provided a tentative list of macroinvertebrate taxa known from the IBP ponds, as of 1977. That faunal list was based on qualitative and quantitative sampling of larger (>1 mm length) aquatic invertebrates, mostly in Ponds E, J, and G (Fig. 2). Emergence of aquatic insects was monitored continuously for several weeks in Pond J, providing adult and pupal material that permitted species-level identification of many insects, including the numerically dominant Chironomidae. During 2007–2010, aquatic macroinvertebrates were again surveyed both quantitatively and qualitatively. Insect emergence was monitored in 2009–2010 to assess the phenology of insect emergence. Instead of the quantitative traps used in 1975–1977, recent emergence monitoring involved standardized dipnet sweeps along the leeward shore of Ponds C and J at 3-day intervals, again providing adult and pupal insect specimens. While the collection methods between the two study periods were slightly different, and approximately four times as many organisms were collected in 2009–2010 than during the studies by Butler et al. (1980), these data still represent an invaluable opportunity to compare species presence-absence and relative abundances. In particular, abundance of all chironomid taxa comprising >0.5% of specimens collected in both 1975–1977 and 2009–2010 was determined and used to rank the taxa from most (1) to least (20) abundant.

RESULTS

If temperatures in Pond C were comparable between the two study periods, weekly data from “late” years (2007–2009) should show a 1:1 relationship with corresponding values from “early” years (1971–1973). We regressed weekly summaries of daily mean and maximum temperatures for the late years against corresponding values for the early years (Fig. 3). Slopes were lower than unity and intercepts greater than zero (based on 95% confidence intervals as a measure of significance). The occurrence of higher mean and maximum temperatures during the late years (2007–2009) relative to the early years (1971–1973) was most pronounced during the beginning (weeks 25 and 26) and end (weeks 31–35) of the open-water season (Fig. 3), whereas mid-summer weeks (notably 27, 28, and 30) plotted closer to the 1:1 line (Fig. 3a, b). Week 29 reflected unexpectedly cool weather during mid-July of 1971 and 1973 (Hobbie 1980).

A second-order polynomial trend line was fit through both temperature summary variables, separately for the early- and late-year data sets, to illustrate the main trends in these time series (Fig. 3d, e). A polynomial model accounted for significantly more variance than a seasonal average for all of the temperature measures, including the daily average ($F_{21,21} = 0.344$, $p = 0.018$), the daily

maximum ($F_{21,21} = 0.315$, $p = 0.011$), and the daily standard deviation ($F_{21,21} = 0.259$, $p = 0.003$). These graphs support the statistical analysis of early versus late year summaries (linear regressions), in that trends in both average and maximum pond temperatures are most different during the earliest (weeks 25 and 26) and latest (weeks 34 and 35) parts of the season but tend to become more similar during the middle of the growing season (Fig. 3d, e). We also found that weekly averages of the daily maximum temperatures corresponded well with weekly averages of the daily mean temperatures, indicating one is a good predictor of the other. Weekly average of the daily maximum temperatures increased at approximately 86% of the rate in the daily mean temperature ($y = 1.21 + 0.86x$; $R^2 = 0.967$).

The variability in daily temperatures as measured by the standard deviation was higher during the beginning (weeks 25 and 26) and end (weeks 34 and 35) of the season for the 2007–2009 data as compared to 1971–1973 but tended to be lower during the middle of the thaw season (weeks 27–30) (Fig. 3c, f).

Data indicate that the IBP ponds in 2008–2010 had significantly higher ammonia, nitrate, and soluble reactive phosphorus concentrations (t tests, $p < 0.01$), as well as marginally higher phytoplankton biomass ($p < 0.10$) than the same ponds in the early 1970s (Fig. 4). There were no

Fig. 3 Comparison of IBP Pond B and/or C temperatures summarized by week of the year. For plots a–c, the numbers associated with points indicate the week of the year, the dark black line indicates the 1:1 relationships, and the dashed line indicates the best fit line from least squares regression with the equation given inset. For plots d–f,

lines represent a fit for a second-order polynomial function justified by our assumption of seasonal rise and decline of average annual temperatures. For model fits, the coefficient of determinations ranged from 0.56 to 0

Fig. 4 Comparison of nutrients and phytoplankton algal biomass at IBP ponds in August 1970–1972 as compared to August 2008–2010. Means ($\pm 1SD$) are from IBP Ponds B, C, and E. Data: Ponds B, C, E in August, only ponds sampled completely at least 2 years per study period

significant differences in total phosphorus or silica concentrations.

Macroinvertebrate communities in the IBP ponds have changed little over the past four decades. All the larger benthic macroinvertebrates reported by Butler et al. (1980) were still common in recent samples, including two trichopteran species: a limnephilid (*Asynarchus* sp.) and a brachycentrid (*Micrasema scissum*) reported but erroneously omitted from a table in that report. Of 27 insect genera found during sampling in the 1970s, 22 genera belonged to the dipteran family Chironomidae. The six highest-ranked chironomid taxa comprised 82 and 86% of total specimens collected in the early and recent studies, respectively, and five of these top taxa were identical in both data sets (Table 1). *Paratanytarsus penicillatus* was the most abundant chironomid in both surveys (>30% relative abundance), followed by two *Tanytarsus* species, and tiny midges in the genus *Corynoneura* that probably represent several species. In general, chironomids with high abundance rankings in the 1970s data were also abundant in the recent samples, although the largest

changes in relative abundance occurred in the most common taxa with *Tanytarsus aquavolans* declining by 10% and *Tanytarsus nearticus* increasing by 17%. *Procladius vesus*, which was common in the 1970s, had the largest decline in rank abundance, from 5th most abundant in the 1970s to 20th in 2009–2010.

Rarer macroinvertebrate taxa (<0.5% of specimens collected) tended to remain rare, although some changed substantially in relative rank. Three such rare taxa, *Chironomus riparius*, *Cricotopus* sp3, and *Limnophyes* sp., increased substantially between the earlier and later study periods, while three of the more abundant species in the 1970s collections (*Procladius vesus*, *Cricotopus tibialis*, and *Cryptochironomus* sp.) were still present but rarer (<0.5%) in the 2009–2010 samples. *Dicrotendipes* sp., present but rare in the 1970s, was not found in 2009–2010. Two new taxa appeared in the Barrow ponds recently: a second, larger *Paratanytarsus* species was found at low density in 2010, while a new tanypod species in the genus *Conchapelopia* appeared in both Ponds C and J, as well as other ponds in the Barrow area, in 2009 and in 2010.

Table 1 Benthic macroinvertebrates collected from tundra ponds near Barrow, AK during 1975–1977 and 2007–2009; taxonomy updated from Table 7-1 in Butler et al. (1980). *P* taxon present, *A* taxon not found. Relative and ranked percent abundances are given for chironomid taxa comprising >0.5% of specimens collected in each data set, based on 2043 adults from emergence trapping (1976–1977, Pond J) and 8660 pupal exuviae from PE sweeps (2009–2010, Ponds C&J)

		Taxon	1976–1977	2009–2010
Turbellaria		Unidentified	P	P
Annelida	Oligochaeta			
	Naididae	<i>Tubifex</i> sp.	P	P
	Propappidae	<i>Propappus</i> sp.	P	P
Hydracarina	Lebertiidae	<i>Lebertia</i> sp.	P	P
Gastropoda	Physidae	<i>Physa</i> sp.	P	P
Insecta	Plecoptera	<i>Nemoura arctica</i>	P	P
	Trichoptera			
	Brachycentridae	<i>Micrasema scissum</i>	P	P
	Limnephilidae	<i>Asynarchus</i> sp.	P	P
	Coleoptera			
	Dytiscidae	<i>Agabus</i> sp.	P	P
		<i>Hydroporus</i> sp.	P	P
	Diptera			
	Chironomidae		Ranked occurrence	
	Podonominae	<i>Trichotanytus alaskensis</i>	9 (2.3%)	10 (1.1%)
	Tanypodinae			
	Macropelopini	<i>Derotanytus aelines</i>	P	P
		<i>Derotanytus alaskensis</i>	15 (0.7%)	16 (0.6%)
		<i>Procladius prolongatus</i>	14 (1.2%)	15 (0.7%)
		<i>Procladius vesus</i>	5 (4.6%)	P
	Pentaneurini	<i>Conchapelopia</i> sp.	A	13(0.9%)
	Chironominae			
	Chironomini	<i>Chironomus prior</i>	12 (1.2%)	12 (0.9%)
		<i>Chironomus tardus</i>	7 (3.7%)	14 (0.8%)
		<i>Chironomus riparius</i>	P	9 (1.3%)
		<i>Chironomus</i> sp4	P	P
		<i>Cryptochironomus</i> sp.	11 (1.3%)	P
		<i>Dicrotendipes</i> sp.	P	A
		<i>Stictochironomus</i> sp.	17 (0.5%)	P
	Tanytarsini	<i>Cladotanytarsus</i> sp.	8 (2.9%)	17 (0.6%)
		<i>Constempellina</i> sp.	6 (4.4%)	6 (7.6%)
		<i>Paratanytarsus penicillatus</i>	1 (30.3%)	1 (30.9%)
		<i>Paratanytarsus</i> sp2	A	P
		<i>Tanytarsus aquavolans</i>	3 (10.1%)	2 (21.1%)
		<i>Tanytarsus nearcticus</i>	2 (25.6%)	4 (8.7%)
	Orthocladiinae			
	Orthocladini	<i>Cricotopus tibialis</i>	10 (1.4%)	18 (0.4%)
		<i>Cricotopus</i> nr <i>perniger</i>	16 (0.5%)	7 (2.3%)
		<i>Cricotopus</i> sp3	P	11 (1.1%)
		<i>Psectrocladius</i> spp.	13 (1.2%)	5 (7.7%)
		<i>Orthocladus</i> spp.	P	P
	Metriocnemini	<i>Bryophenocladus</i> sp.	P	P
		<i>Corynoneura</i> spp.	4 (7.4%)	3 (10.5%)
		<i>Lapposmittia</i> sp.	P	P
		<i>Limnophyes</i> sp.	P	8 (1.4%)
		<i>Mesosmittia</i> sp.	P	P
		<i>Metriocnemus</i> spp.	P	P
		<i>Parakiefferiella</i> spp.	P	P

Differences in the rank abundance or the presence/absence of rarer taxa may reflect increased sampling effort during 2007–2010, when over 8660 specimens were collected versus 2043 specimens in 1976–1977.

DISCUSSION

In summary, these data suggest that the IBP sites have undergone a change in their physical, chemical, and biological characteristics since the 1970s. While these data represent only a snapshot of the conditions found in the early 1970s and 2007–2010, each analysis was performed on at least 3 years of data, thus minimizing the impacts of any potential outliers. In particular, we observed a change in thermal regime, with higher daily mean and maximum pond temperatures relative to available earlier data. These findings are in agreement with much of the work drawing more indirect conclusions based on paleolimnological data (Michelutti et al. 2005; Smol and Douglas 2007b) and are consistent with overall global findings of climate change, and in particular, the arctic amplification. The data also indicate an effect of warming on seasonality, with the greatest differences in warming observed early and late in the season. This supports suggestions by Rouse et al. (1997) that a warming Arctic may lead to lengthened growing seasons and reduced ice cover in aquatic ecosystems. In Barrow, snow melt is occurring earlier than it was in the mid-1960s (Stone et al. 2002). Since many ecological rates are exponentially dependent upon temperature, even small changes in temperatures and growing season can impact ecological processes dramatically.

We also found that the IBP ponds have also become more nutrient-rich since the 1970s, indicating probable temperature-related changes to this ecosystem over the past 40 years. Several studies have indicated that warming permafrost may be releasing nutrients and DOC into Arctic freshwater ecosystems (Wrona et al. 2006). For example, at Toolik Lake, AK, elevated phosphorus in a stream was linked to the mining of gravel for road construction resulting in an abrupt deepening of the active (thawed) layer of soil and increased weathering (Hobbie et al. 1999). And, with degradation of near-surface permafrost, arctic riverine watersheds are exporting more organic and inorganic compounds into the Arctic Ocean (Frey and McCallum 2009).

Increases in nitrogen concentrations in the tundra ponds may also be a result of atmospheric deposition. Nitrogen deposition from the atmosphere has likely doubled in the Arctic since the 1950s (Mayewski et al. 1986; Goto-Azuma and Koerner 2001), and long-range transport of these pollutants has been recorded in Barrow (Jaffe et al. 1991). This deposition of nitrogen may have important implications for

aquatic and terrestrial ecosystem structure and function (Baron et al. 2000), including primary production.

The coincident observed increases in pond temperatures and nutrient concentrations at the IBP ponds are likely contributing to increases in algal primary production. Experimental studies at the IBP ponds in the 1970s support these trends, as researchers suggested that an increase in ambient temperatures (Stanley and Daley 1976) or phosphorus availability (Alexander et al. 1980) could lead to increased algal biomass and production. Nutrients and DOC released from thawing permafrost (Frey and Smith 2005) can drive both autotrophic production and heterotrophic bacterial production. Indeed, we did see a marginal increase in phytoplankton biomass coincident with this increase in nutrients. The implications of these changes to the regional carbon balance are uncertain. If increased algal biomass is not coincident with increases in respiration, then net ecosystem production may tend toward the positive, and thus the ponds may store carbon. However, net heterotrophy has also been observed in nutrient-poor aquatic ecosystems (Algesten et al. 2004; Cole et al. 2007), particularly in small, shallow lakes, and this may lead to carbon efflux from the system, despite an increase in autotrophic production. Given both seasonal and year-to-year variation in limnological variables, a more thorough study is required to support these trends and fully understand their significance.

Aquatic macrophyte biomass also appears to have increased in the Barrow ponds. The aquatic plants *Carex aquatilis* and *Arctophila fulva* dominated primary production in the IBP ponds in the 1970s (Alexander et al. 1980) where they were more productive than in terrestrial sites. Repeat photography has provided anecdotal evidence that dominant species of aquatic vegetation such as *Carex aquatilis* have increased in biomass since the 1970s (Fig. 5). Related studies at sites surrounding the Barrow IBP tundra ponds have also found an increase in graminoid cover in wet tundra areas (Tweedie, unpubl. data). Experiments have indicated that phosphorus limitation plays a more important role than temperature in limiting macrophyte biomass and production in wet sedge tundra (Shaver et al. 1998). However, the causes and consequences of increased macrophyte biomass at the IBP ponds are unclear and require study to provide a more complete understanding of climate-related changes in primary production in aquatic ecosystems in the Arctic.

The macroinvertebrate fauna of the IBP ponds at Barrow has remained relatively stable despite the warming observed to date; however, comparisons to macroinvertebrate communities found in warmer tundra ponds not far inland on the Arctic Coastal Plain suggests that substantial change could occur with increased warming. Cold stenothermic insects like the stonefly *Nemoura arctica* and the podonomid midge

Fig. 5 Photo of IBP Pond B in 1973 (*top*) and 2010 (*bottom*). Metal poles in the bottom photo remain from the 1970s; however, the wooden structures are not in the same location. Note the increased

development on the horizon in 2010 and the increased cover by *Carex aquatilis*, notably in the upper right section of the pond. Photos by John Hobbie (1973) and Vanessa Loughheed (2010)

Trichotanytus alaskensis are still abundant components of the Barrow pond community. These species are absent, however, from ponds at Olak (50 km inland, southeast of Teshekpuk Lake) and near Atqasuk, AK (100 km south of Barrow) (Butler, unpubl. data), where maximum temperatures are higher than in the IBP ponds. This suggests that further warming at Barrow may lead to elimination of these and other taxa through oxygen stress at higher temperatures. Conversely, the predatory midge *Conchapelopia* appears to be a new and relatively abundant addition to the pond fauna at Barrow. This midge has recently been collected from ponds at Atqasuk and Olak, where the pond invertebrate community at the species level differs substantially from that seen at Barrow. Atqasuk ponds host additional predatory invertebrates such as phryganeid caddisflies and larger dytiscid beetles, species that may invade coastal tundra ponds under future climatic scenarios. Further warming of coastal tundra ponds may thus alter the invertebrate community both directly, via elimination of stenothermic taxa and by thermal enhancement of larval insect growth rates, as well as indirectly through altered food-web interactions. The importance of this invertebrate fauna as a food resource for arctic-breeding birds, including passerines, shorebirds, and threatened species like Spectacled and Stellar's Eiders, may also be altered as arctic warming progresses.

While the IBP ponds represent a valuable source of historic data, the site is currently threatened by expansion of the village of Barrow, AK. The IBP ponds, once relatively isolated in the landscape, are now being encroached upon by housing development associated with local population growth at Barrow (Fig. 5). Greater protection and continued monitoring of these invaluable sites will enhance efforts to understand the implications of climate change on Arctic freshwater ecosystems.

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