FEMS Microbiology Ecology Accepted Manuscript

Bacterivory by phototrophic picoplankton and nanoplankton in Arctic waters

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Arctic Ocean / DGGE / mixotrophy / phytoflagellates / picoeukaryotes

Running title: Arctic Ocean mixotrophy

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Abstract

Mixotrophy, the combination of phototrophy and heterotrophy within the same individual, is widespread in oceanic systems. Yet, neither the presence nor ecological impact of mixotrophs has been identified in an Arctic marine environment. We quantified nano- and picoplankton during early autumn in the Beaufort Sea and Canada Basin and determined relative rates of bacterivory by heterotrophs and mixotrophs. Results confirmed previous reports of low microbial biomass for Arctic communities in autumn. The impact of bacterivory was relatively low, ranging from 0.6×10^3 to 42.8×10^3 bacteria mL^{-1} day^{-1}, but it was often dominated by pico- or nano-mixotrophs. From 1-7% of the photosynthetic picoeukaryotes were bacterivorous, while mixotrophic nanoplankton abundance comprised 1-22% of the heterotrophic and 2-32% of the phototrophic nanoplankton abundance, respectively. The estimated daily grazing impact was usually < 5% of the bacterial standing stock, but impacts as high as 25% occurred. Analysis of denaturing gradient gel electrophoresis band patterns indicated that communities from different depths at the same site were appreciably different, and that there was a shift in community diversity at the midpoint of the cruise. Sequence information from DGGE bands reflected microbes related to ones from other Arctic studies, particularly from the Beaufort Sea.

Introduction

Planktonic protists have traditionally been categorized based on their modes of energy and carbon acquisition as either phototrophic (algal) or heterotrophic. However, mixotrophic behavior, whereby organisms combine both of these nutritional modes within a single cell, has been increasingly recognized and documented in aquatic systems (Stoecker, *et al.*, 2009, Sanders, 2011). Phagotrophic feeding behavior occurs in a variety of algal taxa, including chrysophytes, dinoflagellates, prymnesiophytes, rhaphidophytes and cryptophytes, and these organisms have been shown to be ecologically significant as primary producers and consumers (Sanders & Porter, 1988, Unrein, *et al.*, 2007, Jeong, *et al.*, 2010, Jeong, 2011). Mixotrophic nanoplankton (MNAN) can comprise up to 50% of the total phototrophic nanoplankton (cells <20 microns) and be responsible for as much as 86% of the total bacterivory in diverse aquatic habitats (e.g.,Sanders, *et al.*, 1989, Havskum & Riemann, 1996, Havskum & Hansen, 1997, Sanders, *et al.*, 2000).

Although abundances and bacterivory by protists have been examined in the Arctic Ocean, there are no previous investigations of mixotrophy. Earlier studies in the central Arctic Ocean and Chukchi Sea found heterotrophic nanoplankton (HNAN) comprised a large portion of the microbial biomass during summer when flagellates in the 6 – 20 µm size range tended to dominate HNAN biomass (Sherr, *et al.*, 1997); autotrophic plankton biomass during that investigation was dominated by dinoflagellates and miscellaneous flagellates at most stations in the central Arctic, with diatoms making up most of the remaining biomass (Booth & Horner, 1997). However, at some stations in the Canada and Makarov Basins, particularly under thicker ice cover, picophytoflagellates (cells <2.5 microns) tentatively identified as *Micromonas* sp. contributed up to 93% of autotrophic cell abundance and 36% of the autotrophic biomass in

freshly prepared samples (Booth & Horner, 1997, Sherr, *et al.*, 1997).

In the present study the occurrence of mixotrophy in pico- and nano-phytoplankton from Arctic waters was assessed, abundances and bacterivory of heterotrophic and phototrophic protists were determined, and a molecular analysis of the potentially abundant protists was performed using denaturing gradient gel electrophoresis (DGGE). We hypothesized that mixotrophy could be a successful strategy for these Arctic phototrophs based upon the ubiquitous incidence of mixotrophic nanoplankton in subpolar and Antarctic waters (Nygaard & Tobiesen, 1993, Havskum & Riemann, 1996, Bell & Laybourn-Parry, 2003, Moorthi, *et al.*, 2009). We expected that the grazing impacts of mixotrophic organisms could sometimes exceed that of the heterotrophic plankton in the Beaufort Sea the Canada Basin region of the Arctic Ocean.

Materials and methods

Study sites and sampling

Samples to examine protistan abundance and bacterivory were collected at eleven stations within the Beaufort Sea and the Canada Basin of the Arctic Ocean on a cruise of opportunity aboard the icebreaker USCGC Healy in September 2008 (Figure 1). Water was collected from the deep chlorophyll maximum layer (DCM) and at 5 m below the surface during the upcast of a rosette CTD system with 10 L Niskin bottles. These depths were considered to be representative of the mixed surface layer or of a depth (DCM) with potentially increased biomass and activity of microorganisms, including phytoplankton. Exact station locations and physical parameters of the sampling depths from the CTD instruments are presented in Table 1.

Subsamples from each depth were collected immediately for microplankton counts and chlorophyll *a* analysis. Microplankton (ciliates, dinoflagellates, other microflagellates, and

diatoms) were preserved with Lugol's solution (4.5% final concentration) and later settled and enumerated using an inverted microscope at a magnification of 200X. For each chlorophyll *a* determination, 100 mL of whole water were filtered onto a 47 mm GF/F filter (Whatman) and frozen at -20 °C until analyzed. Filters were later extracted in 90% acetone overnight at -20 °C and fluorescence was determined with a Model TD-700 fluorometer (Turner Designs, Sunnyvale, CA, USA).

Preparation of fluorescently labeled bacteria (FLB)

FLB were prepared from cultured *Halomonas halodurans* (~1 µm). These were used successfully in prior studies for the identification of mixotrophic nanoplankton (Sanders, *et al.*, 2000, Moorthi, *et al.*, 2009). *H. halodurans* was inoculated into 1 L of 0.2 µm-filtered and autoclaved seawater enriched with yeast extract (0.1% final concentration). Bacterial cells were grown at room temperature, harvested by centrifugation, washed using filter-sterile seawater (FSW), and then stained with mixing for 3 hr at 64 ºC with 5-(4, 6-dichlorotriazin-2-yl) aminofluorescein (DTAF, Sigma-Aldrich Co., St. Louis, MO, USA) at a concentration of 40 µg mL^{-1}. FLB were then washed 4-5 times with FSW by repeated centrifugation, and finally filtered through sterile 47 mm polycarbonate filters (Whatman, 3 µm pore size) to remove clumps. Concentrations of FLB were determined with epifluorescence microscopy, and aliquots of FLB were stored at -20 ºC until just prior to use in experiments.

Experimental setup and processing

For feeding experiments, triplicate 2 L samples of seawater, prescreened through 100 µm Nitex mesh (Wildlife Supply, Yulee, FL, USA) to remove zooplankton, were incubated in 2.7 L

polycarbonate bottles. Zooplankton were not observed in the experimental bottles or on any of the slides when the samples were counted.

To determine the appropriate addition of tracer particles, bacterial abundance from each depth was initially assessed by epifluorescence microscopy from samples filtered on 25 mm black Poretics polycarbonate filters (0.2 µm pore size). Filters were stained and mounted with cover slips onto glass slides using VectaShield® mounting medium containing DAPI (Vector Laboratories, Inc., Burlingame, CA, USA). Replicate counts for bacteria and fluorescent particle abundances used to calculate grazing impacts were determined with subsamples from each incubation bottle, fixed in 1% formalin and frozen at -20 °C until analysis. Bacteria were enumerated with fluorescence microscopy as described above and fluorescent particles counted by flow cytometry (FACSCalibur, BD Biosciences, San Jose, CA, USA). Our experience was in agreement with Hyun and Yang (2003), who reported a minimum loss of bacterial cells kept frozen in this manner and counted within 2-3 months.

For feeding experiments, fluorescently labeled bacteria (FLB) or 0.6 µm polycarbonate microspheres (Polysciences, Inc., Warrington, PA, USA) were added at approximately 25% of natural bacterial abundance. At Stations 1 and 2, FLB were the only tracers used. At Stations 3 and 4, FLB (1 – 1.2 µm) and microspheres (0.6 µm) were added to seawater in separate incubations. From these experiments it was apparent that picoeukaryotes were not ingesting the larger FLB, and the use of FLB was discontinued in subsequent incubations. In all cases, fluorescent tracers were sonicated immediately prior to addition to disperse particles evenly. The replicate bottles were incubated at 2 ºC under fluorescent lamps at irradiance levels between 2 and 7 X 10^{14} quanta sec^{-1} cm^{-2}, depending on the depth from which the original samples were taken. Light level was measured with a QSL-100 Quantum-Scalar Irradiance meter (Biospherical

Instruments, Inc., San Diego, CA, USA). To determine rates of bacterivory, 100 mL aliquots were taken from the bottles at several time points beginning immediately after particle addition (T0), and fixed using the Lugol's / formaldehyde / $Na_2S_2O_3$ method to prevent egestion (Sherr & Sherr, 1993). After evaluation of initial time course data indicated linear uptake of both FLB and microspheres for 120 minutes, samples were taken at T0 (background correction) and 30 minutes to determine ingestion.

Ingestion rates and abundances of phototrophic, mixotrophic and heterotrophic pico- and nano-plankton were determined from examination of 100 mL of sample filtered onto 25 mm Poretics polycarbonate membranes (3 µm pore size, GE Osmonics, Minnetonka MN, USA). Filters were simultaneously stained and mounted with cover slips on glass slides using VectaShield® as previously described for bacterial counts. To eliminate loss of chlorophyll fluorescence, specimens were frozen at -20 °C until enumeration by epifluorescence microscopy at 1000X magnification onboard the ship. Nanoplankton (3-20 µm) and picoeukaryotes (≤ 2.5 µm) were counted in at least 25 fields per filter (a minimum of 100 and 200 cells for nanoplankton and picoplankton, respectively). Phototrophic and heterotrophic cells were differentiated by the presence or absence of chlorophyll autofluorescence, while mixotrophic cells were defined as those with chlorophyll and at least one ingested fluorescent tracer (FLB or microsphere) after background correction.

Statistical analysis of abundance and feeding data

To examine the potential for environmental factors to affect rates of bacterivory and proportions of mixotrophs, a Spearman correlation analysis was performed using the statistical software program "R" (Hornik, 2011); the arcsine transformation was used on percentage data prior to the

analysis. ANOVA was used to test the effect of tracer particle (FLB, microsphere) on ingestion rates by HNAN and MNAN; relative feeding rates of MNAN and HNAN were examined with a paired comparisons method (Wilcoxon's signed ranks test). Statistical analysis of DGGE results is described in the following section.

Genetic analysis of samples

Twenty liters of water from the surface and DCM were collected directly from the Niskin bottles through 100 µm mesh prefilters onto 47mm GF/F filters (Whatman) and frozen at -20 ºC. Nucleic acids were recovered following the method described in Gast *et al.* (2004). One µl of each sample was amplified for DGGE analysis using the 18S rDNA primers 960FGC and 1200R generating a ~250 bp fragment from the V7 region following the method described in Gast *et al.* (2004). Triplicate PCR reaction products were precipitated and resuspended in a total of 6 µl of sterile distilled water. Nucleic acid concentrations were estimated with a Nanodrop™ 1000 (Thermo Fisher Scientific, Waltham, MA, USA), and about 500 ng of each sample was loaded onto the gradient gel, which was poured and run following the procedure in Gast *et al.* (2004). The image was analyzed using GelComparII (Applied Maths, Austin, TX, USA), and bands detected manually were scored by presence/absence with a tolerance of 1%. Diversity and environmental factors were analyzed using Permanova+ (Anderson, *et al.*, 2008). The DGGE band data matrix was converted to a Bray-Curtis based resemblance matrix, with the environmental factors of site (each station) and depth (surface, deep). Environmental variables included actual depth, site, temperature, PAR, Julian date and salinity. An analysis of variance was performed with Permanova+, and principal coordinates analysis (PCO) was used to visualize the diversity patterns related to environmental variables.

Well-separated bands were picked from the gel using a sterile pipet tip to touch the surface of the gel and then pipetting up and down in 5 µl of sterile distilled water. In our experience, this method has reduced the recovery of multiple bands that occurs when cutting a band from the gel and eluting material from the matrix. The band was reamplified from 2.5 µl of the sample with the non-GC clamped primer set. Samples were precipitated overnight at -20 °C with a final concentration of 0.3 M sodium acetate and 0.6 volumes of 100% isopropanol. They were resuspended in 5 µl of water and 250 ng were sequenced at the Bay Paul facility (MBL) using the non-GC clamped forward primer (960f). Putative band sequence identities were assessed using Blast ™ (GenBank), and we did not observe any potentially chimeric sequences. GenBank no longer accepts sequences shorter than 200bp, and because six of ours are below this limit we have made our sequence data available in the supplemental material (Table S1).

Results

General environmental parameters

The surface salinities and temperatures observed in the Beaufort Sea and the Canada Basin during the study period ranged from 23.15 to 31.49 PSU and -1.63 to 0.4 °C, respectively (Table 1). Photosynthetically active radiation (PAR) measured at the time of sampling ranged from 0.27 to 5.35 quanta cm^{-2} sec^{-1} x 10^{15} at the surface, but never exceeded 0.29 quanta cm^{-2} sec^{-1} x 10^{15} at the chlorophyll maximum depth of any station (Table 1). The general oceanographic parameters of salinity, temperature, and light (Table 1) are within the range of previous reports for the region and the season (Cota, *et al.*, 1996, Lovejoy, *et al.*, 2007, Sherr, *et al.*, 2009, Tremblay, *et al.*, 2009).

Plankton abundances

Overall, abundances of microorganisms were low, as expected for the region and the autumn season. Bacteria were typically present at between 1 – 2 x 10^5 cells mL^{-1} (Table 2). The maximum chlorophyll *a* concentration, observed at the deep chlorophyll maximum of Station 1, was 0.87 µg L^{-1} (Table 2). The abundance of phytoplankton reflected the low chlorophyll concentrations. Diatoms were conspicuously absent from most samples and had a maximum abundance of <1 mL^{-1}. Dinoflagellates were present in all samples, and though the Lugol's-fixed samples used for microplankton enumeration did not enable differentiation between phototrophic and purely heterotrophic individuals, qualitative shipboard observations with epifluorescence microscopy indicated that heterotrophic dinoflagellates tended to be more abundant than phototrophic dinoflagellates by a factor of 2:1 to 3:1. The combined dinoflagellates always numerically dominated the other microflagellates, with a maximum of approximately 7 mL^{-1} (Table 2). Ciliate abundances frequently mirrored the "other microflagellate" category and exceeded 2 mL^{-1} on only two occasions at the surface.

Heterotrophic (HNAN) and phototrophic nanoflagellates (PNAN), mostly in the 4 -6 µm size range, were typically present at 50 – 200 cells mL^{-1}, while mixotrophic nanoplankton (MNAN) abundances were usually at 5 – 20 cells mL^{-1} (Table 3). Photosynthetic picoeukaryotes (Peuk) were the numerically dominant group, and usually exceeded 10^3 cells mL^{-1} (Table 3). Mixotrophic picoeukaryotes (Mpeuk) were identified at every station after the switch was made to smaller (0.6 µm) tracer particles. The abundances of Mpeuk usually exceeded that of the MNAN, sometimes by an order of magnitude (Table 3). However they made up only a very small proportion of the total picoeukaryotes, while MNAN comprised up to 32% of the phototrophic nanoplankton (Table 3). MNAN should also be compared to HNAN since both

contribute to grazing impact on bacteria. MNAN were on average 10% (range 1 – 22%) of the bacterivorous nanoplankton (Table 3).

Ingestion rates and bacterivory impact

Time courses run at the beginning of the cruise indicated that uptake of both FLB and microspheres was linear for the first 120 minutes if incubation, after which ingestion was balanced by digestion and egestion. At Stations 1 and 2, only FLB were used as tracer particles, but at Stations 3 and 4 separate feeding experiments were run with the same communities using either FLB or fluorescent microspheres. Grazing rates by nanoflagellates was greater on microspheres than on FLB in cases where both tracer types were used (Table S2), and ingestion by Mpeuks was detected only in experiments with microspheres. At Stations 3 and 4 where direct comparisons were made, average calculated ingestion rates using microsphere tracers were 0.9 and 3.3 bacteria individual^{-1} h^{-1} for HNAN and MNAN, respectively. Using FLB, the corresponding rates were 0.2 and 2.2 bacteria individual^{-1} h^{-1}. The ingestion rates determined using microspheres were significantly greater than those determined with FLB for both HNAN and MNAN (ANOVA, $p < 0.01$). Polar bacteria tend to be less than 1 µm in size, and the higher rates observed for ingestion of microspheres may reflect size-selective feeding, although larger sized particle ingestion still occurred for the nanoplankton.

Grazing rates were not consistently affected by depth (surface versus DCM). For all three grazing groups, ingestion was greater in surface waters than at the DCM about half the time. Rates were greater in the DCM only twice for HNAN and MNAN and only once for Mpeuk. For the remainder of the incubations, there was no significant difference between depths. Over all experiments, the calculated individual grazing rates were greater for MNAN than for HNAN ($p <$

0.001, Table S2). Using microsphere tracers, the average ingestion rates for HNAN and MNAN were 1.3 and 5.1 bacteria individual^{-1} h^{-1}, respectively. For Mpeuk the average ingestion rate (from microsphere incubations) was 2.9 bacteria individual^{-1} h^{-1}. The reported ingestion rates per cell for MNAN and Mpeuk are inflated relative to those of HNAN due to the method of calculation. HNAN that do not ingest tracers during an experiment can be counted, while potential mixotrophs that are "inactive grazers" usually cannot be distinguished from pure autotrophs. Therefore, the total number of mixotrophs is based only on those ingesting tracers. This does not, however, affect the relative grazing impacts (see discussion).

The potential grazing impact of protists on bacteria ranged from <1 to 25.2 percent of bacterial standing stock per day; the impact was <5% of standing stock d^{-1} in 15 of 20 incubations (Table S3). HNAN, frequently identified as the major planktonic bacterivores, dominated the grazing impact in about half of the experiments, while mixotrophs were more important in the rest (Fig. 2). Mpeuks tended to dominate bacterivory in experiments where the highest total impacts were determined (Table S3). Regarding correlations between ingestion rates and environmental parameters, HNAN rates were positively correlated to light, but there were no other significant relationships (Table S4). MNAN as a proportion of total nanoplankton bacterivores (MNAN/[MNAN+HNAN]) was negatively correlated to salinity and positively correlated to light. Mpeuk as a proportion of Peuk was positively correlated to chlorophyll a, dinoflagellates and total Peuk abundance,

Community structure and comparison

The DGGE results are shown in Figure 3, with the bands successfully recovered for sequencing numbered in panels A and B, and the PCO results in panel C. Generally there were fewer than 5

predominant bands in each sample that were possible to recover for sequencing. Many more were identifiable for community analysis using GelComparII (Applied Maths). Taxonomic affiliation of DGGE band sequences were determined using Blast ™. Sequences recovered include dinoflagellates, diatoms, copepods, dinoflagellate parasites (Syndiniales), and *Micromonas* (a mixotrophic picoeukaryote), with bands from the same position in different samples giving the same sequence results (Table S5). Permanova+ indicated that both depth ($p=0.0086$) and location ($p=0.0001$) were significant in describing the diversity between samples, but that there was no synergistic interaction between the factors ($p=0.7085$). Site and date variables were co-linear, so date was removed from further analyses. The PCO analysis illustrated the effect of site/date and depth on the grouping of samples (Fig. 3C). Separation of two groups along the first axis corresponded to the midpoint of the cruise and described 28.8% of the total variation. The second axis described slightly less of the overall variation (19.3%), and appeared to correspond to depth.

Discussion

Protists play important roles as both primary producers and consumers in southern and northern polar waters (Sherr, *et al.*, 2003, Riedel, *et al.*, 2007, Pearce, *et al.*, 2010), However, previous to the current investigation, nothing was known about mixotrophic protists in the Arctic. Our study confirms the presence of both nano- and pico-planktonic mixotrophs in the Arctic Ocean, and their potential for substantial impact on bacterial communities in the ice-covered Arctic region of the Beaufort Sea in early autumn.

Protistan abundance

Our microscopic investigation of bacterial and protist distribution indicated that densities were low, but within the range of previous reports for the Canada Basin and Beaufort Sea during the late summer to early fall (Table 4). Picophytoplankton were the most abundant protists, typically outnumbering hetero- and auto-trophic nanoplankton by an order of magnitude (Table 3). A small percentage of the picoeukaryotes, from <1 – 7%, were identified as mixotrophic by ingestion of fluorescent tracers, but at most stations they were still more abundant than mixotrophic nanoplankton (MNAN) identified in the same manner (Table 3). At least one cultured strain of the picoprasinophyte *Micromonas* was previously found to be phagotrophic (González, *et al.*, 1993), and most of the mixotrophic picoeukaryotes enumerated with epifluorescence microscopy in our study resembled the "typical *Micromonas*-like cell stained with DAPI" as presented in a color photomicrograph in Lovejoy *et al.* (2007). Coupled with the frequent occurrence of bands in the DGGE gels that were linked to *Micromonas* (Fig. 3, Table S5), our data indicate potential for relatively large impacts by this picoprasinophyte as a bacterivore in the Arctic ecosystem at this time. Furthermore, the wide-spread occurrence of *Micromonas* (Sherr, *et al.*, 2003, Not, *et al.*, 2005, Lovejoy, *et al.*, 2007, Tremblay, *et al.*, 2009) suggests that mixotrophy could be common in the Arctic throughout the year.

After picoplankton, HNAN were the next most numerous protists, though HNAN abundance was usually within a factor of two of combined PNAN and MNAN assemblages. Sherr et al. (1997) also found that the <5 µm HNAN were numerically dominant heterotrophs, but noted that the 6 – 20 µm size class tended to dominate heterotrophic biomass in integrated samples (0 to 50 m) along a cruise track from the Chukchi Sea to the Nansen Basin from July through August (Sherr, *et al.*, 1997, Wheeler, *et al.*, 1997). The microplankton size-fraction in

295 our samples was always dominated by dinoflagellates and ciliates, though abundances were on
296 the low end of ranges reported previously for arctic and sub-arctic waters (Sherr, *et al.*, 1997,
297 Levinsen, *et al.*, 2000, Strom, *et al.*, 2007, Vaqué, *et al.*, 2008). Diatoms were observed at very
298 low abundances, if at all, in our microscope counts (Table 2). Likewise, Sherr et al. (2003)
299 reported Arctic Ocean winter diatom abundances ≤ 1 cell mL^{-1} and Terrado et al. (2009) reported
300 diatoms represented only 4% of autumn clone library sequences in Franklin Bay.
301
302 **Protistan diversity**
303 Low biomass as indicated by the microscopic and pigment observations would not necessarily
304 indicate low diversity. However, microscopy suggested that only a limited number of taxa were
305 present, with diatoms absent from most samples. DGGE also yielded only a few predominant
306 bands for each sample, although many faint bands were also present.
307 When the recovered Arctic DGGE bands were compared with those recovered from the
308 Antarctic (Gast, *et al.*, 2004) at a level of 97% similarity, the only overlap in sequence
309 information was for the copepod *Oithona*. Prior genetic studies of microbial eukaryotes in the
310 Arctic have used both DGGE and clone libraries to examine the community structure (Lovejoy,
311 *et al.*, 2006, Hamilton, *et al.*, 2008, Terrado, *et al.*, 2009, Tremblay, *et al.*, 2009, Bachy, *et al.*,
312 2011, Lovejoy & Potvin, 2011). The DGGE fragment used in this study targeted a different
313 region of the ribosomal gene than some of those projects, and most of those studies have been
314 directed towards the <5 micrometer size group, yet there are similarities. The groups commonly
315 identified by molecular diversity surveys of Arctic waters included alveolates (ciliates,
316 dinoflagellates, group I & II alveolates), unidentified marine stramenopile genotypes (MAST),
317 dictyophytes, prasinophytes, haptophytes, diatoms, bolidophytes, cryptophytes and the newly

identified picobiliphytes. In common with this work, other studies have also reported the abundance and wide distribution of *Micromonas* (Sherr, *et al.*, 2003, Lovejoy, *et al.*, 2007, Terrado, *et al.*, 2008), as well as the diatom *Chaetoceros*, novel alveolate group II Syndiniales, and other dinoflagellates.

Mixotrophy, bacterivory, and grazing impacts

The ubiquitous occurrence of mixotrophic plankton found in the current study and in a recent reports from Antarctic waters (Moorthi, *et al.*, 2009) suggest that mixotrophy may be a successful strategy for some phytoplankton in polar marine environments. The potential benefits of particle ingestion by phytoplankton include the acquisition of organic carbon, energy, major nutrients, and/or micronutrients including vitamins and trace metals (e.g.Caron, *et al.*, 1993, Nygaard & Tobiesen, 1993, Maranger, *et al.*, 1998). If, as has been suggested by Tremblay and Gagnon (2009), primary production in seasonally ice-free waters of the Arctic Ocean is controlled by nitrogen supply, then mixotrophy there may act as a competitive mechanism for nitrogen uptake. Increased mixotrophy under nutrient limitation has been noted for nanoplankton and suggested for picoeukaryotes in other marine systems (Nygaard & Tobiesen, 1993, Zubkov & Tarran, 2008), although the environmental drivers of mixotrophic behavior are likely to vary with species.

In the Ross Sea Antarctica, photosynthetic and heterotrophic nanoplankton range over three orders of magnitude from about 2 mL^{-1} to 7 x 10^3 mL^{-1} and peak in austral summer (Dennett, *et al.*, 2001, Moorthi, *et al.*, 2009). MNAN were typically <200 mL^{-1} in plankton assemblages south of the Polar Front of the Southern Ocean, but still comprised 8% - 42% of bacterivorous nanoplankton in the water column, and 5-10% of phototrophic and 3-15% of

341 phagotrophic nanoflagellates present in ice cores (Moorthi, *et al.*, 2009). The abundance of
342 MNAN during the Arctic autumn ranged from 2 to 300 mL^{-1} and comprised the same relative
343 abundances when compared to total heterotrophic (1-22%) and total phototrophic (2-32%)
344 nanoplankton (Table 3) as was observed during austral summer. A major difference in our
345 studies of mixotrophs in the Arctic and Southern Oceans was the abundance and impact of the
346 picophytoplankton. While phototrophic picoeukaryotes were not noted in our Antarctic samples,
347 they numerically dominated many of the Arctic samples and were important as bacterivores.
348 Food size appeared to be of consequence for the mixotrophic picoeukaryotes; ingestion
349 was observed when the 0.6 µm microspheres were used, but never when the 1 – 1.2 µm FLB
350 were offered. Grazing by nanoflagellates on microspheres also was significantly greater than on
351 FLB ($p < 0.001$, ANOVA), though absolute differences were not large. Overall, the mixotrophic
352 community (MNAN and Mpeuks) ingested 2X as many bacteria-sized particles as the
353 heterotrophs, indicating that they had an equivalent or greater grazing impact on bacteria as that
354 of the more traditional (heterotrophic) consumer population.
355 As a community, the pico- and nano-plankton removed from $0.06 – 2.6 \times 10^4$ bacteria
356 mL^{-1} d^{-1}, dependent to a large degree on the abundance of picoeukaryotes. This compares to a
357 grazing impact, estimated using FLB, of $0.1 – 4.6 \times 10^4$ bacteria mL^{-1} d^{-1} by heterotrophic
358 plankton during the Arctic summer (Sherr, *et al.*, 1997). Anderson & Rivkin (2001) used the
359 dilution technique to examine bacterivory, and also noted significant grazing impact during early
360 summer blooms and during winter in Resolute Bay, Northwest Territories, Canada.
361 This is the first study to demonstrate mixotrophy by phytoflagellates in Arctic waters, and
362 the data suggest that a *Micromonas*-like picoprasinophyte was an important bacterivore in the
363 Canada Basin during autumn. The role of picoeukaryotes as quantitatively important grazers has

been demonstrated only once previously – in the North Atlantic Ocean (Zubkov & Tarran, 2008), though it was conjectured to occur in the Arctic (Sherr, *et al.*, 2003). Since these picoprasinphytes are known to persist through winter darkness and grow exponentially from late winter to early spring (Lovejoy, *et al.*, 2007), phagotrophy may contribute importantly to survival during winter darkness and give the organisms a relatively large seed population at the beginning of the spring growth period. If global climate change freshens the Arctic Ocean as proposed by Li *et al.* (2009), the impact of picoeukaryotes as bacterivores may become especially important.

RWS and RJG contributed equally to this paper

Acknowledgements

We gratefully acknowledge the captain and crew of USCGC Healy for logistical support. Funding for participation in the 2008 cruise was provided by the Woods Hole Oceanographic Institution Arctic Research Initiative, with additional support from National Science Foundation Grants OPP-0838847 (RWS) and OPP-0838955 (RJG). We thank Zaid McKee-Krisberg and Scott Fay, respectively, for assistance with R statistical software and Generic Mapping Tools (GMT) used to create Fig 1.

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Table 1. Sampling stations, date (in 2008), locations (lat/long), collection depth (m), water column depth Z_{max} (m), salinity (PSU), temperature (°C), and light (quanta cm^{-2} sec^{-1} x 10^{15}) measurements from the CTD sensor.

Station	Date	Location	Depth	Z_{max}	Salinity	Temp	PAR
1	7 Sept	77 24.53 N 151 18.84 W	5	3840	27.43	-1.12	2.33
			60		30.99	-1.08	0.08
2	8 Sept	79 34.20 N 147 13.75 W	5	3820	27.97	-1.39	4.63
			50		31.24	-1.45	0.21
3	11/12 Sept	80 36.97 N 130 21.72 W	5	3500	29.24	-1.56	0.02
			50		30.71	-1.44	0.01
4	13 Sept	80 03.84 N 132 04.51 W	5	3620	27.69	-1.48	5.10
			50		30.72	-1.54	0.28
5	15 Sept	79 36.21 N 146 50.63 W	5	3800	27.11	-1.44	2.72
			37		30.68	-1.28	0.29
6	19 Sept	78 32.16 N 124 57.08 W	5	2450	30.14	-1.63	0.55
			60		30.49	-1.59	0.02
8	21 Sept	78 24.5 N 134 35.2 W	5	3650	21.68	-1.42	5.35
			30		24.40	-1.06	0.85
			70		25.05	-1.34	0.09
9	24 Sept	78 17.69 N 140 56.22 W	5	3800	26.98	-1.45	1.27
			45		30.79	-1.18	0.05
10	27 Sept	76 24.32 N 131 7.58 W	5	2770	27.52	-1.48	0.27
			55		31.04	-1.29	0.15
11	29 Sept	72 14.196 N 140 55.53 W	5	2990	23.15	0.40	1.31
			75		30.55	-0.65	0.03

Table 2. Station microbial characteristics. Chlorophyll a concentration (μg l^{-1}), heterotrophic and autotrophic microplankton abundance (ml^{-1}), and bacterial abundance (x 10^5 ml^{-1}) in the Beaufort Sea. * = not observed.

Station	Depth (m)	Chl *a*	Ciliates	Dino-flagellates	Other Flagellates	Centric Diatoms	Pennate Diatoms	Bacteria
1	5	0.16	0.51	2.54	*	*	0.20	5.50
	60	0.87	0.91	3.86	*	0.30	0.20	–
2	5	0.20	0.25	2.85	2.85	*	*	2.20
	50	0.51	0.44	4.50	0.19	0.06	*	1.81
3	5	0.29	2.03	7.25	0.25	*	0.10	1.80
	50	0.42	0.36	2.18	0.30	*	*	2.20
4	5	0.28	2.22	5.71	1.84	*	0.25	2.49
	60	0.30	0.41	3.25	0.86	*	0.05	1.93
5	5	0.44	1.78	7.00	1.42	*	0.10	1.70
	37	0.54	1.37	5.68	1.83	*	0.05	1.98
6	5	0.20	0.36	1.37	0.41	*	*	1.84
	60	0.35	0.91	2.43	0.71	*	*	2.18
8	5	0.26	1.22	5.17	0.30	0.05	*	1.33
	30	0.29	0.36	2.23	*	*	*	1.17
	70	0.34	0.10	2.33	0.20	*	*	1.60
9	5	0.24	1.07	5.88	1.62	0.05	*	1.65
	45	0.40	0.51	3.25	0.81	*	*	1.37
10	5	0.23	0.91	2.94	1.12	*	*	1.31
	55	0.30	0.20	2.33	0.61	*	*	2.51
11	5	0.22	1.32	4.26	0.71	*	*	1.65
	55	0.28	0.41	1.62	0.30	0.10	*	1.24

Table 3. Abundances (no. ml^{-1} ± S.E.) of heterotrophic nanoflagellates (HNAN), phototrophic nanoflagellates (PNAN), mixotrophic nanoflagellates (MNAN), photosynthetic picoeukaryotes (Peuk) and mixotrophic picoeukaryotes (Mpeuk), and mixotrophs as a percentage of all similarly-sized phototrophs and heterotrophs. Picoeukaryotes did not ingest FLB, and microspheres were not used until Station 3. Note that the percentage calculations include mixotrophs as part of the total nano- and pico-plankton abundance.

STA	Depth (m)	HNAN	PNAN	MNAN	Peuk	Mpeuk	% of PNAN	% of HNAN	% of Peuk
1	5	93 ± 5	25 ± 4	7 ± 1	–	–	21	7	–
2	5	45 ± 6	15 ± 5	2 ± 1	–	–	13	5	–
	50	23 ± 4	82 ± 8	3 ± 0	–	–	4	12	–
3	5	66 ± 15	71 ± 6	11 ± 3	1 217 ± 164	30 ± 5	14	15	2
	50	52 ± 10	48 ± 17	5 ± 1	872 ± 283	18 ± 4	9	9	2
4	5	90 ± 3	54 ± 5	3 ± 1	1 901 ± 108	56 ± 22	5	3	3
	60	57 ± 15	34 ± 3	16 ± 1	880 ± 45	6 ± 6	32	22	1
5	5	121 ± 30	46 ± 11	19 ± 2	2 757 ± 242	220 ± 16	30	14	7
	37	143 ± 20	77 ± 22	16 ± 6	2 807 ± 251	155 ± 17	17	10	5

Table 3, p 2

STA	Depth (m)	HNAN	PNAN	MNAN	Peuk	Mpeuk	% of PNAN	% of HNAN	% of Peuk
6	5	129 ± 13	97 ± 17	36 ± 3	444 ± 77	9 ± 5	27	22	2
	60	126 ± 23	143 ± 35	22 ± 8	324 ± 59	18 ± 6	13	15	5
8	5	130 ± 12	45 ± 5	8 ± 4	3 021 ± 310	87 ± 3	15	6	3
	30	102 ± 10	126 ± 18	10 ± 5	1 598 ± 54	61 ± 2	8	9	4
	70	108 ± 21	91 ± 10	5 ± 1	952 ± 101	4 ± 3	5	4	< 1
9	5	206 ± 36	106 ± 9	2 ± 1	3 047 ± 695	139 ± 7	2	1	4
	47	178 ± 13	100 ± 7	19 ± 3	1 523 ± 123	77 ± 4	16	10	5
10	5	97 ± 26	51 ± 18	8 ± 3	1 862 ± 290	12 ± 6	13	8	1
	55	114 ± 9	65 ± 4	2 ± 2	914 ± 278	16 ± 6	3	2	2
11	5	193 ± 7	45 ± 11	13 ± 1	2 011 ± 208	0	22	6	< 1
	75	66 ± 6	25 ± 12	7 ± 3	1 061 ± 161	25 ± 18	23	10	2

Table 4. Abundances of microorganisms reported from Arctic waters.

Location	Dates	Bacteria (# ml^{-1})	Synecho (# ml^{-1})	HNAN (# ml^{-1})	Peuk (# ml^{-1})	PNAN (# ml^{-1})	Ciliates (# ml^{-1})	Dinoflag (# ml^{-1})
S. Canada Basin [1]	Nov 1997-May 98	1-3 x 10^5		90 - 490	"hundreds"	3 – 1500	0.1 - 2	1 - 12
Beaufort Sea/ NW Passage [2]	Feb-May 2004				10 – 9500			
Canadian Arctic/ Franklin Bay [3]	Dec 2003-May 04	1-5 x 10^5		200 - 600		30 -450	0.1 - 1.3	
Central Arctic [4]	July-Sept 1994				1000 – 10000	42 - 910		9 - 105
Central Arctic [5]	July-Sept 1994	4-12 x 10^5	Not observed	250 - 1900	1000 – 10000	Not reported	0.1 - 17	0.1 - 39
Chukchi Plateau/ Mendeleyev Basin [1]	June-Sept 1998	2-7 x 10^5		210 – 2300	1000 - 28000	100 – 28000	0.1 - 2	1 - 12
North Baffin Bay [6]	Aug-Sept 2005		0 - 17		660 – 10365			
NW Passage [6]	Aug-Sept 2005		1 - 70		860 – 18360			
Beaufort Sea/ Amundsen Gulf [6]	Aug-Sept 2005		1 - 120		150 – 16990			
North Baffin Bay [7]	Sept-Oct 1999				18 – 4070	130 – 3080		
Mackenzie Shelf/ Amundsen Gulf [8]	Sept-Oct 2002		470 – 2425		215 -2110			
Beaufort Sea/ Canada Basin [9]	Sept 2008	1-5 x 10^5	Not observed	20 - 200	320 – 3050	15 - 140	0.2 - 2.2	1 - 7

Abbreviations: Synecho, *Synechococcus* spp.; HNAN, heterotrophic nanoflagellates; Peuk, picoeukaryotes; PNAN, phototrophic nanoflagellates; Dinoflag, dinoflagellates. [1] Sherr et al. 2003, [2] Lovejoy et al. 2007, [3] Vaqué et al. 2008, [4] Booth & Horner 1997, [5] Sherr et al. 1997 (pooled from upper 50 m, same cruise as Booth & Horner 1997), [6] Tremblay et al. 2009, [7] Mostajir et al. 2001, [8] Waleron et al. 2007, [9] This study.

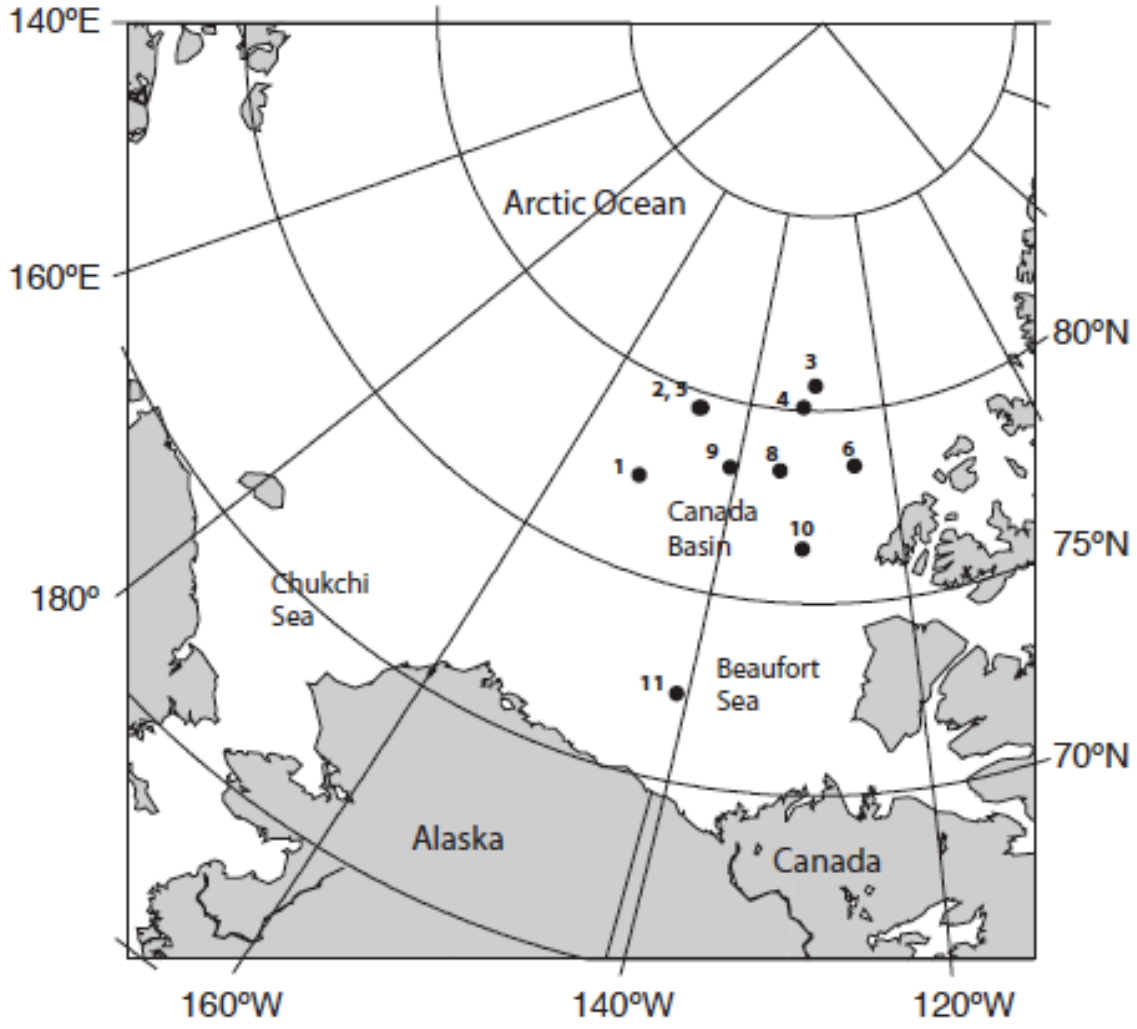
Figure Legends

Figure 1. Location of sampling sites within the Beaufort Sea and Canada Basin of the Arctic Ocean. North pole is at the upper right corner of the chart.

Figure 2. Relative impact of mixotrophic nanoflagellates (MNAN), mixotrophic picoeukaryotes (Mpeuk) and heterotrophic nanoflagellates (HNAN) as grazers of bacterioplankton.

Figure 3. Denaturing gradient gel electrophoresis results from the Beaufort Sea and the Canada Basin. A) Samples from stations 1-6 and B) Samples from stations 6-11 (numbers indicate bands successfully recovered and sequenced). C) Principal coordinates analysis plot with environmental variable vectors at the right; deep = deep chlorophyll maximum, surface = 5m, numbers indicate each station. Axis 1 represents 28.8% of the total variation, while axis 2 represents 19.3% of the total. These appear to represent the variables of site/location and depth respectively.

Figure 1. Location of sampling sites within the Beaufort Sea and Canada Basin. North pole is at the upper right corner of the chart.



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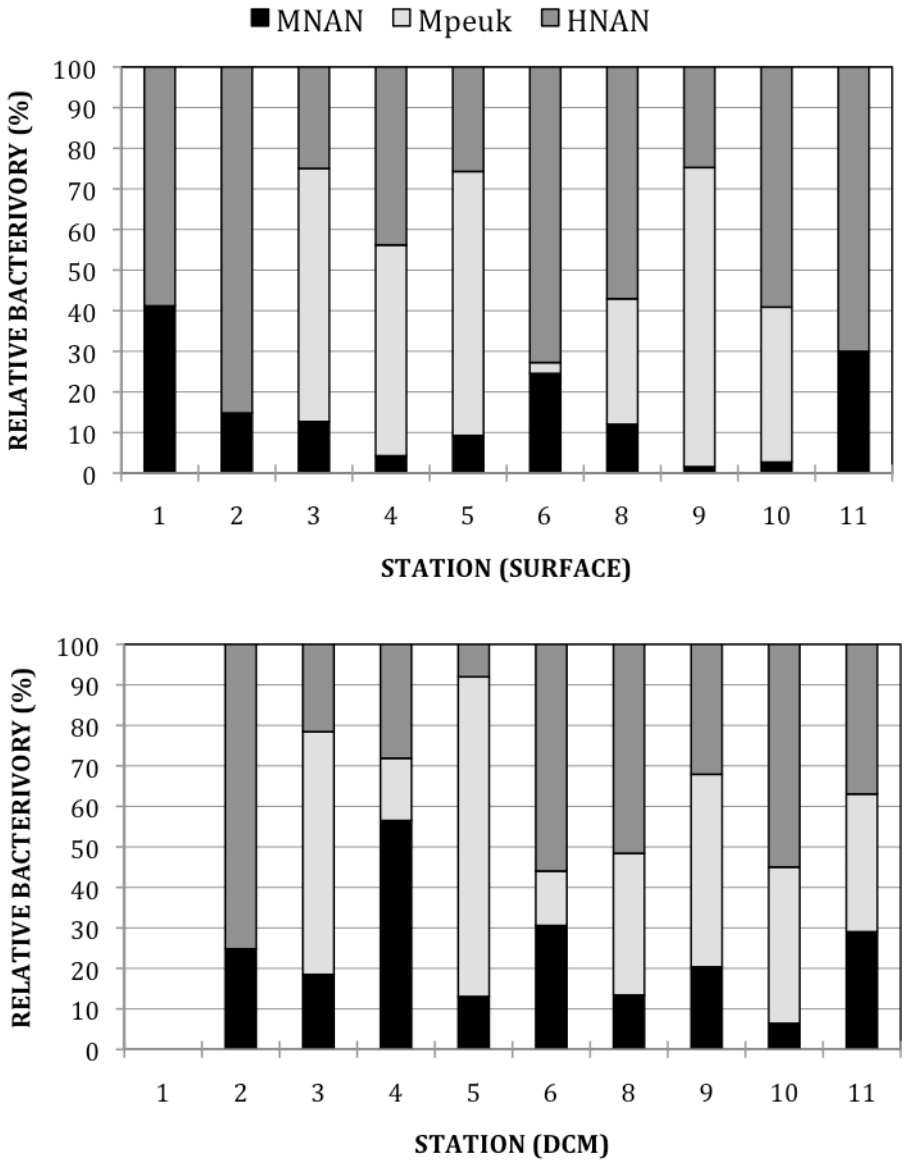

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