Biogeosciences Discuss., 12, 11751–11795, 2015
www.biogeosciences-discuss.net/12/11751/2015/
doi:10.5194/bgd-12-11751-2015

Biogeosciences
Discussions
Open Access

Controls on microalgal community structures in cryoconite holes upon high Arctic glaciers, Svalbard

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Received: 27 May 2015 – Accepted: 4 July 2015 – Published: 29 July 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Glaciers are known to harbor surprisingly complex ecosystems. On their surface, distinct cylindrical holes filled with meltwater and sediments are considered as hot spots for microbial life. The present paper addresses possible biological interactions within the community of prokaryotic cyanobacteria and eukaryotic microalgae (microalgae) and relations to their potential grazers, additional to their environmental controls. Svalbard glaciers with substantial allochthonous input of material from local sources reveal high microalgal densities. Small valley glaciers with high sediment coverages and high impact of birds show high biomasses and support a high biological diversity. Invertebrate grazer densities do not show any significant negative correlation with microalgal abundances, but a positive correlation with eukaryotic microalgae. Most microalgae found in this study form large colonies (< 10 cells, or $> 25\,\mu$m), which may protect them against invertebrate grazing. This finding rather indicates grazing as a positive control on eukaryotic microalgae by nutrient recycling. Density differences between the eukaryotic microalgae and prokaryotic cyanobacteria and their high distinction in RDA and PCA analyses indicate that these two groups are in strong contrast. Eukaryotic microalgae occurred mainly in unstable cryoconite holes with high sediment loads, high N : P ratios, and a high impact of bird guano, as a proxy for nutrients. In these environments autochthonous nitrogen fixation appears to be negligible. Selective wind transport of Oscillatoriales via soil and dust particles is proposed to explain their dominance in cryoconites further away from the glacier margins. We propose that, for the studied glaciers, nutrient levels related to recycling of limiting nutrients is the main factor driving variation in the community structure of microalgae and grazers.

1 Introduction

Cryoconite holes are cylindrical cavities filled with meltwater and biological active sediments found on the surface of glaciers worldwide. Their diameter can range between a few centimeters and several meters (MacDonnel and Fitzsimons, 2008). They are mainly created by air-borne sediment inputs into small depressions, which result in an increased melt rate caused by a decreased albedo (McIntyre, 1984; Fountain et al., 2004). Even though they are ice-free only during the short Arctic summer, cryoconite holes can cover a large part of the ablation zone and contribute significantly to the glacier runoff (Hodson et al., 2008). Recently reviewed studies also demonstrated that glacial ecosystems have a significant impact on the global carbon cycle (Stibal et al., 2012a). Common approaches tried to find environmental controls on the net ecosystem productivity, but the biotic controls have often been overlooked. We hypothesize that the biotic controls have similar dynamics to temperate lakes, where primary productivity is not solely controlled by environmental parameters (bottom-up), but also by grazing pressure (top-down) (Sterner, 1986).

Cryoconite holes represent ultraoligotrophic environments (Hodson et al., 2008) inhabited only by microorganisms, which are able to adapt to many environmental challenges associated with a life on the surface of glaciers. Filamentous phototrophic cyanobacteria and mostly coccal heterotrophic bacteria are shown to act as ecosystem engineers within the cryoconites, capable of forming distinct dark granules up to 3 mm thick in diameter (Takeuchi et al., 2001; Langford et al., 2010). These granules provide a substrate for growth of surprisingly high biomasses and diversities of bacteria, cyanobacteria, eukaryotic microalgae and protozoa (Mueller et al., 2001; Christner et al., 2003; Cameron et al., 2012). Additionally, invertebrates mainly comprised of tardigrades and rotifers have been found, inhabiting cryoconite holes on glaciers worldwide (De Smet, and van Rompu, 1994; Groongard and McInnes, 1999; Säwström et al., 2002; Porazinska et al., 2004; Zawierucha et al., 2014). The species diversity of these grazing invertebrates is relatively low and relatively well-known but their ecological role in the cryoconite community has not been addressed yet. It is believed that they act as top predators in a microbial food web consisting of both grazing and carnivorous species (De Smet and van Rompu, 1994).

In temperate freshwater systems grazing is known to have a substantial effect on microalgal communities (to avoid duplication of terms, “microalgae” in the text also includes Cyanobacteria, unless further specified). For example, Sterner (1986) described two effects of invertebrate grazing on microalgal communities. Firstly, selective feeding can suppress the population of the preferred food organisms. Secondly, invertebrate grazing is suitable to release nutrients from microalgae biomasses and enhance the growth of otherwise nutrient limited organisms. In contrast to the crustacean dominated grazer communities in temperate ponds, preying on relatively large organisms, the cryoconite communities are known to consist of much smaller grazers. Generally, Arctic freshwater ponds are characterized by a food web with a few trophic levels, dominated by crustacean grazers with short generation times, due to the short growing season (Rautio et al., 2011). The zoobenthos community is thought to obtain its carbon from benthic primary production and associated bacterial growth (Rautio et al., 2011). Another effect of grazing has been described by Vanormelingen et al. (2009), who observed enlarged colonies of a *Coenobium* species as possible adaptation to grazing. Bdelloid rotifers are known as size selective filtration feeders for small cells (Ricci and Balsamo, 2000; Devetter, 2009) and are common in cryoconite holes (Zawierucha et al., 2014). Tardigrades, another part of the grazer community in cryoconite holes, are able to prey on much larger organisms (Nelson and Marley, 2000). Ciliates in cryoconite holes can generally act as grazers on microalgae and bacteria, or as prey for larger metazoans (Sinistro et al., 2006), but Mieczan et al. (2013) found that carnivorous and bacterivorous ciliates prevail in Antarctic cryoconites. Another difference between temperate and polar food webs is the slower growth rate of herbivores compared to microalgae in cold environments, which is known to lead to a weak and delayed top down control in habitats with low temperatures (Rose and Caron, 2007).

So far, none of the mechanisms described above has been studied in cryoconite holes and the significance of trophic interactions in cryoconite holes is yet unknown.

For the present study microalgae can be classified into four dominant groups differing in their adaptations to a life on glaciers. Filamentous cyanobacteria, usually consisting of Oscillatoriales (*Leptolyngbya* sp. and *Phormidium* sp.) (Mueller et al., 2001), are capable of stabilizing the cryoconite granules which, reversely, can protect the microalgae from physical stress (Takeuchi et al., 2001). Also a small amount of atmospheric nitrogen can be fixed by these non-heterocystous oscillatorian cyanobacteria (Bergman et al., 1997; Telling et al., 2011). Nostocales, usually consisting of *Nostoc* sp. (Mueller et al., 2001) can form big colonies as protection against environmental stresses and act as storage for nutrients and carbon (Li and Gao, 2007). They also form heterocysts capable of efficient atmospheric nitrogen fixation (Kumar et al., 2010). Chlorophyceae, mainly consisting of *Chlamydomonas nivalis* (Mueller et al., 2001), are well adapted to high light intensities by the production and storage of photoprotective pigments (Bidigare et al., 1993). Furthermore, snow microalgae are known to migrate to favorable microhabitats (Kavecka, 1986). Zygnematophycea are another group of eukaryotic microalgae capable of production and storage of photoprotective pigments in a moveable vacuole (Remias et al., 2012; Yallop et al., 2012). In summary, cyanobacteria on glaciers are well adapted to nitrogen limitations, whereas green microalgae are better adapted to high light intensities and environmental disturbances. Hence, the stability and nutrient levels should influence the ratio of green microalgae to cyanobacteria and competition is likely to occur.

The aim of the present study was to investigate the importance of environmental controls compared to biological interactions (grazing, competition) on the microalgal community structure and to discuss possible mechanisms involved. The community structures and densities of microalgae and their possible grazers are estimated and environmental parameters were measured. Correlation analyses were then applied to assess possible controls on the microalgal community structure and their relative importance.

2 Methods

2.1 Site description and sampling

Between July and August 2014, 62 cryoconite holes on the three valley glaciers Nordenskiöldbreen, Hørbyebreen (HC), and Ebbabreen (E) (Table 1, Fig. 1) around Petuniabukta and Adolfbukta on Svalbard (76°30′–80°30′ N and 10–35° E) were sampled. The three glaciers were all valley glaciers. Nordenskiöldbreen was separated into 4 sampling sites: (1) close to the glacier margin and a bird colony on the peninsula Retrettøya (NR), (2) on the southern site of the glacier (NC), (3) on a central plateau (NI), and (4) on the bottom of a drained supraglacial lake (NL). On Hørbyebreen, 10 samples were taken from the central part and 6 samples in 25–100 m elevation intervals. On Ebbabreen, 6 samples were collected every 25–100 m in height. As will be described, the sites vary in some environmental factors, such as nutrient availability, stability (e.g. water depth), and isolation of the cryoconite holes. For an overview of the studied glaciers see Rachlewicz et al. (2007).

On the central part of Hørbyebreen and the southern site of Nordenskiöldbreen 5 cryoconite holes were sampled 4 times throughout the summer season (June–August) in order to test for seasonal variations. Five additional cryoconite holes on these sites were sampled at the beginning and the end of the season to test for possible impacts of the repeated sampling (Control). From all other sites 6 samples were taken. The samples taken, and measurements done, are summarized in Table 1.

Cryoconite sediment was collected into a 0.5 L polyethylene bottle equipped with a two-way lid and two siphons in order to produce underpressure (Fig. 2). Sediments in a defined area within a 4.5 cm plastic ring were taken. All sampling equipment was washed with meltwater from the sampling site prior to the sampling.

2.2 Density estimations of invertebrates and ciliates

Densities of tardigrades, rotifers and big ciliates (> 25 µm) were estimated as the number of individuals per cm^2 of cryoconite sediment layer. The fresh sample was transferred into a clean 120 mL beaker. The sample was left for at least 30 min to settle and the supernatant was removed until 100 mL of the sludge remained. The sample was then homogenized in the laboratory by shaking and a 10–20 mL subsample was taken and transferred into a 10 cm petri dish with parallel lines on the bottom with a distance of 5 mm. In this subsample, the number of 5 functional grazers or predators was counted (tardigrades, bdelloid rotifers (*Macrotrachella* sp., *Adineta* sp.), carnivorous monogonont rotifers (*Encentrum* sp.), and big ciliates) with a stereomicroscope. All samples were analyzed within 24 h after the sampling and stored in the dark at temperatures below 4 °C. In all sampling sites, only actively moving individuals were counted. For tardigrades and rotifers, species level identification was carried out in 1–3 random sites per glacier.

2.3 Density estimations of microalgae

Microalgal biovolumes were estimated using an epifluorescence microscope for cyanobacteria and light microscopy for eukaryotic microalgae as described by Kaštovská et al. (2005). For the counting, 0.25 g of wet sediment was diluted with 3 mL of the meltwater from the analyzed sample and crushed in order to homogenize the granules. 40 µL of this suspension was transferred onto a microscopic slide and at least 200 cells were counted and measured. Basic geometric equations for cylinders with hemispherical ends and spheres were applied to calculate the biovolume per wet mass of sediment. After measuring the total sediment mass in the predefined area, it was possible to calculate the densities as biovolumes per area (µm^3 cm^{-2} of cryoconite sediment layer). Additionally, the biovolumes were separated into different size classes based on estimated limits for grazing by filtrating organisms. The estimations are based on the common size of grazers (100–200 µm) and their feeding apparati (buccal tube of tardigrades 5–10 µm, filtrating organ opening of rotifers 25–50 µm) in the samples of this study. Microalgal biovolumes of single cells ≤ 10 µm, single cells > 10 µm, colonies ≤ 10 cells, colonies > 10 cells, filaments ≤ 25 µm, filaments > 25 µm were separated in order to visualize the spectrum of possible food items. The mean and median sizes of the colonies and cells were estimated. All densities are given in $\mu m^3\,cm^{-2}$ of cryoconite sediment layer, since photosynthetic activity is thought to be limited to the first few µm of the sediment surface. Errors of this method related to the dilution, determination, measurements and counting are described by Mueller et al. (2001). For the study of population dynamics, the microscopic approach is preferred to molecular methods since the taxonomic resolution is not as important as accurate density estimations of functional groups. A PCR-bias in genetic methods would, however, lead to a higher uncertainty in density estimations. Nevertheless, the cyanobacterial community structures of Hørbyebreen (HC) and Nordenskiöldbreen (NR) were compared with previous measurements of the prokaryotic community structure based on MiSeq Illumina sequencing of the V3-V4 regions of the 16S rRNA genes in 2012. This additional genetic method helps to validate the microscopy derived estimates and gives an estimate of the abundances of additional bacteria and cyanobacterial genera. The most dominant genera were then compared to previously found *nif*H genes, important for nitrogen fixation, in the NCBI database (Gaer et al., 2010). The functional cyanobacteria groups in this study are; Nostocales as heterocystous cyanobacteria, and Oscillatoriales as filamentous cyanobacteria without heterocysts, but with the ability to stabilize cryoconite granules. The eukaryotic microalgal groups are; Chlorophycea and Zygnematophyceae. Diatoms and Chroococcales were excluded from the analysis due to their low abundances and the related inaccuracy of biovolume estimations in dilutions.

2.4 Environmental variables

As proxies for the age and stability of the hole, water depth was measured with a ruler. The water content of the sediments was calculated as percentage of weight loss of saturated sediments after drying at 50 °C for 12 h. The total organic matter (TOM) content was estimated as the weight loss of the dried sediments after dry combustion at 450 °C for 5 h. The sediment load was estimated as the total mass of cryoconite sediments within a defined area. The sediment coverage of Nordenskiöldbreen (NC) and Hørbyebreen (HC) was estimated using aerial pictures taken by a multicopter using ImageJ after Irvine-Fynn et al. (2010). The elevation and distance to the closest deglaciated land was measured using a hand held GPS and topographic maps from 1990 with an error of about 25 m related to the mapping, and an underestimation of approximately 75 m related to glacial retreats. The time of the sampling was calculated as summer degree days (sdd). Sdds are commonly used to model the surface runoff of glaciers (Braithwaite, 1995) and thus a good indicator of the environmental disturbance on the supraglacial system, related to time. As a proxy for nutrient inputs the impact of birds was estimated as ranks between 0 and 3 based on, (1) the presence of birds or bird remnants (excrements, carcasses), and (2) the distance to bird colonies. An impact of 0 refers to a site with no signs of birds or excrements, far away from any bird colonies, whereas an impact of 3 means a site with birds resting on the glacier with excrements around and a bird colony nearby. For the chemical analyses of cryoconite sediments, ammonium and ammonia (NH_3-N and NH_4^+-N (NH_x-N)) were measured by the gas diffusion method using a FIA LACHAT QC 8500 (Lachat Instruments, USA) after Karlberg and Twengstrom (1983) (Application note ASN 50-0187, Tecator, ISO 11732), and the total mineralized phosphorous (TP) was measured after Kopáček and Hejzlar (1995), while bioavailable orthophosphate (PO_4^{2-}-P) was measured photometrically after Mehlich (1984). For the chemical analysis of the meltwater, total organic and inorganic carbon (TOC, TIC) were measured from a filter, using an elemental analyzer. Due to the stability of chemical properties in cryoconites, previously observed (Porazinska et al., 2004), all nutrients were measured once during the season and in a mix of sediments from different cryoconites of each site.

2.5 Statistical analysis

In order to test for differences between the sites and possible controls, multivariate and univariate statistics were applied using different statistical programs. Log transformed data were used for all ordination analyses. Analyses of similarities (ANOSIM) were performed, using past (Hammer et al., 2001), for comparing the community structures between the sites, controls and treatments, and different sampling times within the same cryoconite hole, using Bray–Curtis dissimilarities. The null hypothesis was rejected if $p < 0.05$. p values of multiple tests were corrected after the false discovery rate. A one-way ANOVA followed by a Tukey honest significant difference test was applied, using R (R Development Core Team, 2008), to test for differences of environmental variables, and mean and median sizes of microalgae between the sampling sites. For direct correlation between grazer and microalgae, correlation analysis of $\log(x + 1)$ transformed densities and standardized microalgal densities ($x 10^{-6}$) were applied using R. Multiple linear regression models using untransformed (Oscillatoriales), $\log(x + 1)$ transformed (other microalgae) data and assuming a poisson distribution were used to assess the effects of grazer densities on the mean and median sizes of the different microalgal groups.

For a more detailed analysis of possible biotic interactions, a principal component analysis (PCA) was performed using CANOCO 5.03. A partial redundancy analysis (RDA) was applied in order to test for environmental controls, using CANOCO 5.03., as a linear constrained ordination method. Prior to the ordination, a detrended correspondence analysis (DCA) was used to test whether a linear ordination is appropriate. A gradient length of 2.4 SD supported a linear model. Interactive-forward-selection-covariates was used in order to build a model, which only includes the best explanatory variables and to avoid the problem of colinearity. After the ordination, a permutation test based on r^2 values with 999 permutations enabled testing the amount of variation explained by the model and the explanatory variables. In order to test for environmental controls, a model using the environmental variables as explanatory variables and the spatial variables as co-variables was used.

3 Results

3.1 Differences between sites

Differences between the sites were found in their environments and their community structures as shown in Fig. 3a–c and Table 2. Hørbyebreen (HC) shows the highest proportion and concentration of cyanobacteria (88 %, $238 \times 10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$) compared to eukaryotic green microalgae ($31 \times 10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$) and the highest densities of all microalgae based on the microscopic counts ($270 \times 10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$) (Fig. 3a). The Retrettøya (NR) community differs from all other sites because of a microalgal community dominated by green microalgae ($209 \times 10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$) (Fig. 3a). The sites Nordenskiöldbreen – Plateau (NI) and Nordenskiöldbreen – supraglacial lake (NL), which were furthest away from deglaciated land, have the highest proportion of Oscillatoriales (56 and 71 %). The other sites are rather similar with a cyanobacteria dominated community (71–68 %).

16S rRNA sequence based abundances of cyanobacteria in 2012 show, overall, similar patterns as observed in 2014 via epifluorescence microscopy (Fig. 3a and c). Cyanobacteria constitute a substantial part of the prokaryotic community (21 and 26 % on Nordenskiöldbreen, and 39 % on Hørbyebreen of all 16S reads) (Fig. 3c). The most dominant cyanobacteria in the 16S reads were *Arthronema* sp., *Microcoleus* sp. and *Nostoc* spp., *Calothrix* spp., *Symploca* sp., and *Leptolyngbya* sp. were also abundant genera (Fig. 3c).

The rest of the bacterial diversity in the 16S reads is mainly represented by Proteobacteria, Bacteroidetes, and Actinobacteria. Other potentially diazotrophic bacteria included bacteria of the genera *Clostridium*, and *Ralstonia*. The only additional phototrophic bacteria found in the 16S reads was the green non-sulfur bacteria group of

Chloroflexi (< 1 %). In a few samples of this study (1–3 per glacier), microalgae have been identified to genus level by microscopy. Cyanobacteria of the genera of *Nostoc*, *Leptolyngbya*, *Phormidium*, and *Microcoleus* prevailed in the microscopic counts. The most abundant cyanobacteria genera in the 16S reads, *Arthronema* sp. and *Calothrix* sp., have not been recognized via microscopy. The most dominant green microalgae included *Chlamydomonas nivalis*, *Ancylonema nordenskioldii*, *Cylindrocystis brebissonii* and *Mesotaenium berggrenii*.

Regarding the grazers, in most sites tardigrades and rotifers were equally abundant (1–5 Ind. cm^{-2}) (Fig. 3b). Only on Ebbabreen (E) did the grazer community have higher densities of tardigrades (25 Ind. cm^{-2}) compared to the other sites (Fig. 3b). A seasonal change in the community structure was found between the first and last sampling dates on Hørbyebreen (HC) ($p = 0.0384$), but no difference between the repeatedly sampled cryoconite holes and their controls, and no seasonal variation of the community structures were found.

As for the microalgae, in a few samples, invertebrates were identified to genus or species by microscopy. The most dominant rotifers belonged to the *Macrotrachella insolita* group, ranging between 1 (NL) and 4 (HC) Ind. cm^{-2}. Particularly *M. musculosa* made up the largest proportion of this group. Also, a few individuals of *Adineta vaga* (0.4 (NR) – 0.9 (E) Ind. cm^{-2}), and *Encentrum* sp. (0 (NL, NR) – 0.3 (E) Ind. cm^{-2}) were found. The most frequent tardigrades found on all sampled glaciers were *Pilatobiotus recamieri* and *Hypsibius dujardini*. Rarely found were also *Hypsibius* cf. *arcticus* and the genus *Isohypsibius*. Tardigrade species were not identified immediately in the field and were thus not quantified. Ciliates were not identified to species or genera.

A more precise description of differences in environmental variables for each site is given in Table 3. Overall, the variation in environmental factors and community structures within one glacier (Nordenskiöldbreen: NC – main site, NR, NI, NL) is often higher than the variation between the glaciers (Tables 2 and 3).

The sites NC and HC have similar nitrogen and phosphorus concentrations and ratios. The nutrient data for NR and NI showed generally higher N : P ratios. The

TOC : TIC ratio on Hørbyebreen (HC) compared to Nordenskiöldbreen (NC) seems to be higher.

Hørbyebreen is characterized by the lowest water depth and highest sediment coverage, but Nordenskiöldbreen, and particularly the Retrettøya site (NR) had the highest sediments loads (sediment thickness in cryoconite), the highest water content and the highest concentration of organic matter. The deepest cryoconite holes were found on the upper plateau of Nordenskiöldbreen (NI). The cryoconite holes next to Retrettøya are closest to deglaciated land and have the highest sediment load and impact of birds, since they were right next to a colony of Arctic terns. Also a high number of Black-legged Kittiwakes used to rest on the glacier when the low tide sweeps the icebergs out of the fjord. The supraglacial lake is the farthest from any deglaciated land and cryoconite holes in this area were particularly deep with the lowest sediment load and organic matter content.

3.2 Possible biotic interactions

Principal component analysis (PCA) (Fig. 4) was used to look for possible correlations between all groups and linear Pearson's correlation (Table 4) for the correlation between invertebrate grazer densities and their proposed prey. The abundance of grazers were significantly correlated with an increase in Zygnemales concentrations ($r^2 = 0.29$–0.31) (Table 4). Rotifers were positively correlated with both Zygnemales and Chlorococcales, and tardigrades only with the usually larger Zygnemales (Table 4). In contrast, both groups of cyanobacteria (Oscillatoriales and Nostocales) were not correlated with either tardigrades or rotifers.

The PCA shows that the first axis explains most of the variation for green microalgae and grazers, but both of the cyanobacterial groups are mainly explained by the second axis (Fig. 4). This indicates different controls on eukaryotic microalgae and grazers, in contrast to cyanobacteria. Besides the positive correlation between grazers and eukaryotic microalgae, the PCA suggests another positive correlation between the green microalgae and consumer groups (ciliates, rotifers and tardigrades).

The distribution of mean and median sizes of different microalgae as possible food sources for grazers (Figs. 3, 5a and b) show in general that most eukaryotic microalgae are larger than the suggested filtration limit for rotifers, and most cyanobacteria form colonies which are larger than 10 µm (cells) or longer than 30 µm.

An ANOVA showed that the communities of the supraglacial pond (NL) have significantly longer filaments of Oscillatoriales and a generalized linear model assuming a poisson distribution shows that the median length of Zygnemales is significantly different between the different sites.

Multiple linear regressions with $\log(x+1)$ transformed (Nostocales), and untransformed (Oscillatoriales) data and generalized multiple linear regressions assuming a poisson distribution (Zygnemales, Chlorococcales) show that the densities of the filtrating rotifers are negatively related to the average length of Oscillatoriales and the median length of Zygnemales (Table 5). Ciliates are positively correlated with the mean size of Oscillatoriales.

3.3 Environmental controls

Possible environmental controls were tested by redundancy analysis (RDA). Firstly, a RDA with temporal (time of sampling) and spatial (glacier, and place on glacier) variables as explanatory variables showed that these variables can only explain 10.7 % of the total variation. The spatial variables in this model explained 84.9 % of the variability. In total, it appears that the cryoconite communities are influenced by spatial and only to a smaller degree by temporal variation. The part of explained variation in the final model is shown in Table 6.

In a partial RDA, all environmental variables and time were used as explanatory variables and spatial variables were used as co-variables. After interactive-forward-selection-covariates, a model with three significant explanatory variables remained, as shown in Table 7. The impact of birds (bird) (17.5 %), the elevation (14.1 %) and sediment load (sedmass) (10.5 %) explained most of the variation in the model (42.2 %).

The RDA biplot (Fig. 6) shows that the sediment load strongly decreases with elevation. If no bird remnants are present, cyanobacteria dominated. Eukaryotic microalgae (Chlorophyceae and Zygnematophyceae) are positively related to the sediment load. The grazer abundances are positively related to possible fertilization by birds. All axes of the biplot explain a significant ($p = 0.02$, $F = 2.9$) part of the total variation.

4 Discussion

4.1 Microalgae distribution

The current study showed a high spatial variability of the abundance of different microalgal groups. High eukaryotic microalgae to cyanobacteria ratios were observed in environments close to the sea, deglaciated land, or bird colonies with low nitrogen levels. Significantly higher proportions of cyanobacteria were found further away from possible nitrogen sources. Oscillatoriales dominated over Nostocales the furthest away from any deglaciated land.

Three different selective mechanisms are proposed to explain the observed variation of microalgal groups among different environments. The first selection mechanism is wind transport of dust and soil particles, including cyanobacteria and nutrients (Broady, 1996; Porazinska et al., 2004). This wind transport is proposed to be selective for certain cyanobacteria groups. We propose that selection occurs because polar cyanobacteria are often associated with dust in soil, and thus easily transported by wind (Broady, 1996). Furthermore, they are well adapted to desiccation and cryoinjuries which frequently occur during wind transport and on glaciers and could explain their usual dominance in polar freshwater habitats (Tang et al., 1997; Šabacká and Elster, 2006) and in our samples. Hence, thin trichomes of Oscillatoriales (*Leptolyngbya*, *Arthronema* e.g.) are likely to be easily transported on glacial surfaces by this way. Nitrogen input by dust is proposed to be of rather low impact, if the dust originates from adjacent slopes, but having a relatively high impact if it originates from tundra soil

(Stibal et al., 2006). The second selection criterion is the nitrogen input in the form of nitrate, nitrite and ammonia, or ammonium which selects for eukaryotic microalgae. The most important inputs are most likely atmospheric inorganic nitrogen stored in snow and ice followed by sea spray or bird guano, tundra soil and moraine dust with the least hypothesized importance. While there are high inputs of tundra soil and bird guano, we propose an insignificant role of autochthonous N_2 fixation. The third selection mechanism is the stability of the environment, where eukaryotic microalgae are better adapted to quickly changing environments due to their quick growth, photoprotection by complex adaptation processes of their photosystems and mobility in the case of snow microalgae.

All three mechanisms together can explain the distribution described above. Namely, high eukaryotic microalgae concentrations occur in an unstable environment with high concentrations of bioavailable nitrogen and a high impact of birds. High Oscillatoriales proportions are found further away from the glacier margins, but still at low concentrations due to their less efficient pathways of N_2 fixation. Higher Nostocales proportions occur where nutrient inputs are limited to dust from adjacent moraines, which would transport Oscillatoriales, but much less bioavailable nitrogen for the growth of eukaryotic microalgae.

The dominance of *Arthronema* sp. and *Calothrix* sp. in the 16S reads was unexpected. Both genera are usually absent or rarely found in cryoconites (Mueller et al., 2001) and the microscopic identifications did not show high abundances of these genera in our samples. In fact, *Arthronema* sp. has not been found in cryoconites at all. *Arthronema gygaxiana* is known to be distributed globally in freshwater and soil habitats, including glacier forefields (Casmatta et al., 2005; Frey et al., 2013). Hence, the presence of this species in our analyses from 2012 is possible. However, sequence similarity analysis of previously analyzed 16S rRNA genes of *Arthronema* spp. and the other dominant species in our reads using ARB (Quast et al., 2013) showed a high heterogeneity between strains. One strain was more closely related to *Leptolyngbya antarctica* than to all other strains. Hence, we interpret the 16S reads of cyanobacteria only to the genus level. The ecological interpretations in the present paper focus on broader taxonomic levels of microscopically identified cyanobacteria.

4.2 Geographic properties

The valley glaciers on Svalbard typically have a substantial allochthonous input of sediment and nutrients from local sources due to their small size compared to larger ice sheets. Microalgal densities found in this study are between 1.8 (NI) and 7.8 (HC) times higher than previously measured on the Greenland ice sheet (GrIS) (Stibal et al., 2006, 2011, 2012b). It is clear that small valley glaciers with high sediment coverages and high impact of birds contain usually higher nutrient levels and thus a higher biomass and a higher biological diversity than larger ice sheets. However, the cyanobacterial proportion within the phototrophic cells (73 %) is comparable with the findings from the GrIS (66 %) (Stibal et al., 2006).

Eukaryotic microalgae contributed with biovolumes of $14\text{–}32 \times 10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$ (14–29 %) on most sites, except near Retrettøya (NR) ($209 \times 10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$, 83 %) where the contribution was small. Similar values have been observed by Stibal et al. (2006) on the GrIS. In direct comparison, most sites in the present study are enriched in cyanobacteria compared to the GrIS, except for the exceptional site NR. Only 17 % of the phototrophic cells at this site were cyanobacteria, which would rather fit to the values of medial moraines on the GrIS (24 %) measured by Stibal et al. (2006), but the general concentration of phototrophs at NR is two orders of magnitude higher compared to the medial moraines. This finding may indicate a system with high productivity due to sufficient nutrient input and sunlight compared to the moraines or more isolated cryoconites, but a different community structure. Most of the eukaryotic microalgae found are known as ice- or snow microalgae, and possible reasons for their accumulation at the NR site will be explained later.

Spatial variability between close glaciers has also been found. Our data indicate high variability in the community structure within various parts of one glacier. Stibal et al. (2012b) found different environmental controls on microbial communities in cryoconite holes at different altitudes on the Greenland ice sheet. Chemical variables were mostly explained by physical and/or geographic parameters. The altitude, slope, distance to the closest deglaciated land, debris coverage and suggested ecological zones (glacier margin, bare ice, slush) explained most of the variability within the microbial community structure and the measured chemical parameters. Since the present study did not cover a comparable range of slopes, no effect of the slope was found. For the debris coverage, elevation and distance to the closest deglaciated land, the proxies measured and used were elevation and sediment load for the habitat stability and age and bird impact for external nutrients. Each showed a significant impact on the microalgal community structure and on their proposed consumers (grazer). Similar environmental controls on grazer abundances have been observed in Antarctica (Porazinska et al., 2004) with significant effects of sediment load and elevation.

The low abundances of cyanobacteria on glacial surfaces (Lutz et al., 2014) also suggest a weaker adaptation to quickly changing and unstable environments. Such a negative relation between cyanobacteria presence and high sediment loads in lower elevations in cryoconite holes is clearly visible. It is well know that cyanobacteria are slow growing (Tang et al., 1997), which means that they are more sensitive to disturbance, as shown by the negative relation with the sediment load. On the contrary, eukaryotic microalgae are fast growing and more resistant to disturbance by sediment load. In fact, Cook et al. (2010) found that cryoconite granules usually form a single grain layer between 0.04 and 0.20 $\mathrm{g\,cm^{-2}}$ by lateral thermal conductivity if time allows. This means that a thick sediment layer indicates a younger, unstable cryoconite hole. The sediment load of the present study ranged between 0.161 $\mathrm{g\,cm^{-2}}$ at NI and 0.396 $\mathrm{g\,cm^{-2}}$ at NR. These values are, compared to Cook's et al. (2010) study, on the higher end and indicate rather unstable environments. Furthermore, some microalgal cells might be recently mixed into deeper layers of the sediment.

4.3 Nutrient inputs

The external nutrient inputs by birds together with the stability of the cryoconite holes play an additional role. The N : P ratio below 16 : 1 (Redfield, 1958) on HC and NC suggest a nitrogen limited environment where cyanobacteria dominate, whereas NI and NR with higher N : P ratios indicate, on the contrary, a phosphorous limited environment, where eukaryotic microalgae prevail. However, the number of replicates did not allow for reliable statistical tests on the exact nutrient levels. Also, Telling et al. (2011) found that phosphorous is generally the main limiting nutrient on glaciers and that nitrogen is usually introduced by snow and rain (atmospheric nitrogen) rather than by cyanobacterial nitrogen fixation. Previous research performed in Greenland by Stibal et al. (2006) did not show a clear effect of nutrient levels on cryoconite hole microbial diversity and organic matter production, either. This research rather proposed that physical factors influence the nutrient conditions on glacial surfaces. In fact, Stibal et al. (2006) showed that soil texture, water content and pH are the main factors, controlling microalgal community structures in supraglacial environments. In the present study, it appears that these factors did not play an important role in our small valley glaciers.

The cyanobacterial diversity seems to be controlled by completely different variables as indicated by the PCA (Fig. 4), in which eukaryotic microalgae and grazers were mostly explained by the first and cyanobacteria by the second axes, respectively. Considering the nitrogen fixation capability of cyanobacteria, it is clear that these organisms are dominant in nitrogen limited environments. This is indicated by the negative relation to the impact of birds and a high N : P ratio on the site at Retrettøya (NR) with the highest impact of birds.

4.4 Nitrogen fixation

Microalgae, including cyanobacteria, are an important part of the microbial community in cryoconite sediments. In fact, in our samples cyanobacteria biovolumes represent about 49–250 × 10^{-6} $\mu m^3\,cm^{-2}$ of the cryoconite sediment layer. In the 16S rRNA reads, 20–39 % of the prokaryotic community are cyanobacteria and within the microalgae community mostly between 71 and 88 %. The finding that all cyanobacteria identified have had heterocysts or close relatives with the *nif*H gene and their dominance in often nitrogen depleted cryoconites supports the hypothesis that sediment associated cyanobacteria act as drivers of this ecosystem in respect to inorganic carbon and nitrogen fixation in nutrient depleted areas.

In particular, the high abundances of cyanobacteria in the cryoconite community suggest that the nitrogen limitation in these ultraoligotrophic environments may be compensated by atmospheric nitrogen fixation. In fact, all cyanobacteria identified via microscopy and 16S sequencing are known to have relatives with *nif*H genes for nitrogen fixation in their genome (Isojarvi et al., 2015; Paul et al., 2014; Starkenburg et al., 2011; Steward et al., 2004; Taghavi et al., 2013). Only for *Arthronema* sp. is previous genome analysis lacking. However, in several studies it has also been proposed that allochthonous atmospheric nitrogen inputs is two orders of magnitude higher than autochthonous nitrogen fixation, which would mean that cryoconites are mainly phosphorous limited (Hodson et al., 2010; Telling et al., 2011; Žárský et al., 2013). Nevertheless, in ultraoligotrophic samples far from the impact of nesting or resting birds, cyanobacteria are thought to be crucial for atmospheric nitrogen storage on the glacier. Telling et al. (2012) already showed the importance of cyanobacterial nitrogen fixation on the Greenland Ice Sheet (GrIS). Eventually, nitrogen fixation may enhance the production of organic matter and expolymeric substances, which is proposed to support higher trophic levels, such as the metazoan grazers (Telling et al., 2011; Žárský et al., 2013) and heterotrophic bacteria (Decleyre et al., 2015).

4.5 Temporal variability

Temporal variability in the microalgal community structures has been measured for the first time in this study. An ANOSIM analysis did not show any seasonal variation, but the RDA suggests a small temporal variability within one season, which is masked by environmental and spatial factors. The temporal impact is statistically significant, but the explanatory importance is negligible. A similar study by Musilova et al. (2015) also found no temporal trend in the microbial community structure on the Greenland ice sheet. However, their method was solely based on 16S tag sequencing, replicates were lacking and their results should be treated carefully. Also, the cyanobacterial proportion in the microbial community was smaller (3–29 %), compared to our study, which may be caused by a different system on the Greenland ice sheet, or by different primers used. The overall community structure is fairly similar. The fact that both studies used different methods, different taxa and different habitats and still came to the same conclusion highly supports a cryoconite community of eukaryotes and prokaryotes which is not considerably influenced by temporal factors. One possibility for this temporal homogeneity is the short summer season and the strong selective pressure.

4.6 Microalgae size and grazing resistance

Most cyanobacteria found in this study form large colonies (< 10 cells, or > 25 µm), which may protect them against grazing by filtration (Sand-Jensen, 2014). In fact, we found a negative correlation between the average length of trichomes of Oscillatoriales and filtrating rotifers. A similar effect has been found on the colony sizes and dimensions of a *Coenobium* species in interconnected freshwater ponds and has been found to be an adaptation to grazing pressure (Vanormelingen et al., 2009). Ciliates are positively related to the mean length of Oscillatoriales, which may be explained by a shared positive effect for Oscillatoriales and Ciliates if the filtrating grazers are less abundant. Perhaps it is caused by a lack of competition for their bacterivorous diet with the filtrating feeding strategy of rotifers. Regarding the environmental factors, it is known that filamentous cyanobacteria in cryoconite holes act as ecosystem engineers by stabilizing relatively large granules, which are more stable and can support mutualistic relationships with heterotrophic bacteria (Takeuchi et al., 2001). For this function, a certain size would be necessary, considering average diameters of cryoconite granules above

1 mm. The large colonies of Nostocales can be an adaptation to typical environmental stresses, such as freezing and nutrient limitation. Li and Gao (2007) showed that larger colonies of *Nostoc* sp. can be more tolerant to freezing and desiccation and can be capable of storing nutrients. Green microalgae are, in general, relatively large and occur mainly as single cells. Grazer abundances were not correlated to their sizes (Table 7).

4.7 Cyanobacteria vs. eukaryotic microalgae

Differences between the eukaryotic microalgal and cyanobacterial densities at the studied sites and their high distinction in the RDA and PCA analyses indicates that these two groups are in strong contrast. Green microalgae occurred mainly in cryoconite holes with high sediment loads and a high impact of bird guano, as a proxy for nutrients. Furthermore, green microalgae are most dominant in habitats with higher NH_x-N and PN/TP ratios above the Redfield (16 : 1). This indicates that green microalgae prefer habitats with high nitrogen levels and can survive in unstable environments, where the sediment thickness does not yet reach an equilibrium depth (Cook et al., 2010). This is usually the case in glacial ablation zones at lower elevations, as was proved by the lower sediment load at the sites furthest away from the glacier margin (NI, NL), compared to the site close to the margin (NR) (Table 3). The eukaryotic microalgae found in this study consisted of taxa which are referred to as ice- (Zygnemales), and snow- (Chlorococcales) microalgae, respectively. These two groups are well adapted to living on the fast changing glacial ice and melting snow. This adaptation is connected with high light intensities, survival in unstable conditions, and an efficient use of nutrient pulses by quick growth, which has recently been shown by Telling et al. (2014). All these adaptations are most likely also favorable in unstable cryoconite holes with higher nutrient levels, where green microalgae can compete with the usually more dominant cyanobacteria (Stibal et al., 2006). Tang et al. (1997) and Šabacká and Elster (2006) suggested that cyanobacteria are, despite their slow growth, usually dominant in polar freshwater systems, due to their adaptation to freezing and desiccation. However, eukaryotic microalgae may become dominant in unstable environments, due to their higher growth rate. Another explanation could be that the green microalgae found in this study were accidentally imported to the cryoconite holes. Since these microalgal groups usually occur on glacial surfaces, unstable cryoconite holes with thick sediment layers at lower elevations would accumulate more supraglacial organisms by meltwater inflow.

4.8 Invertebrate grazing

Grazer densities did not show any significant negative correlation with microalgal abundances, but only a positive correlation with green microalgae. This can either indicate that grazing has a positive impact on green microalgal densities, perhaps by nutrient recycling, which should have the same effect as the impact of birds, or by shared environmental preferences. The latter is more likely, since the PCA (Fig. 4) showed very similar environmental gradients for green microalgae and cyanobacteria, and the impact of birds is positively related to grazer abundances, and green microalgal densities. Hence, nutrient availability seems to impact both green microalgae and grazers. One explanation could be that those grazers are mainly feeding on smaller heterotrophic bacteria, and only to a lesser extent on microalgae. In this case, high nutrient levels would support, besides the higher densities of green microalgae, also high densities of heterotrophic bacteria. The bdelloid rotifer species and genera found in this study are, indeed, known to be bacterivorous (Devetter, 2009). The tardigrades found in this study are expected to be bacterivorous or algivorous based on the morphology of their buccal tube. A few grazers found during epifluorescence microscopy had cyanobacterial cells in their stomach. In order to clarify this open question, future studies should include the densities of heterotrophic prokaryotes and an extended study of the stomach contents of grazers.

Trophic interactions between grazers are also possible, as pointed out by Cameron et al. (2012) and Zawierucha et al. (2014), but only positive correlations have been found between the major groups. The same positive correlation between tardigrade and rotifer abundances has been observed in Antarctica (Porazinska et al., 2004). This indicates in general shared food sources and low competition. In fact, the genera found in this study include grazers with different feeding strategies, including filtration feeders (*Macrotrachella* sp.), grasping feeders (*Adineta* cf. *vaga*), carnivores (*Encentrum* sp.), and omnivorous grasping tardigrades (*Hypsibius* sp., *Isohypsibius* sp.), which may reduce competition. Some organisms, such as small rotifers and ciliates, can act as a food source for larger omnivorous or carnivorous species. Correlation analyses of these genera were not possible due to the low abundances of rare species and the related inaccuracy in estimation of their densities in diluted samples.

5 Conclusions

The spatial and temporal variability in microalgae and grazer community structures in cryoconite holes on central Svalbard has been studied. Environmental parameters, such as sediment load, elevation (proxy for cryoconite stability and age), and the impact of birds (proxy for nutrient inputs), explained most of the variation in the community structure. Different adaptations of various microalgae groups to ultraoligotrophic or unstable habitats are proposed to explain these effects. Grazer abundances were not found to be negatively correlated to any microalgae densities, but to some of their sizes. We propose that grazing pressure by filtrating rotifers probably led to longer cells and colonies as adaptations to size selective feeding.

A positive correlation between rotifers and green microalgae densities has also been found. A mainly bacterivorous diet for most of the grazers is suggested to explain this positive correlation. In fact, shared environmental preferences of green microalgae and bacteria for high nutrient levels are hypothesized to explain this correlation. Further experiments including bacterial abundances and the stomach contents of grazers could help to test this novel hypothesis. Microalgae have been found to occur in very high abundances with cyanobacteria making up a substantial part of the prokaryotic community, indicating their importance as ecosystem engineers. Also, the high abundances of tardigrades, rotifers, and ciliates, including genera with different feeding strategies, have been found and suggest a complex food web between more trophic levels than measured in the present study. Feeding experiments and analysis of stomach contents may help to bring a more detailed picture of this yet hardly known food web.

The Supplement related to this article is available online at doi:10.5194/bgd-12-11751-2015-supplement.

Author contributions. T. R. Vonnahme, J. Elster, J. D. Žárský, M. Devetter, and M. Šabacká contributed to the preparation of the manuscript, analysis of the data, and experimental design. J. Elster coordinated the study. The community structures were assessed by T.R. Vonnahme, M. Devetter (microscopy), and M. Šabacká (16s rRNA). Environmental parameters were measured by T. R. Vonnahme and J. D. Žárský. Nutrient analyses were performed by J. D. Žárský and M. Šabacká.

Acknowledgements. The field and lab work in the Czech Republic and on Svalbard was funded by the Ministry of Education, Youth and Sports of the Czech Republic: (1) CzechPolar – Czech polar stations, construction and logistic expenses (LM2010009), (2) establishing of working team and conditions for education in the field of polar ecology and life in extreme environments, (No.CZ.1.07/2.2.00/28.0190), and a long-term research development project of the Academy of Sciences of the Czech Republic RVO 67985939. The project No.CZ.1.07/2.2.00/28.0190 was also funded by the European Social Fund and from the governmental budget of the Czech Republic. Furthermore, we want to thank Jan Kavan for help with the logistics, Jana Šnokhousová for her laboratory assistance and Patrick Downes and Keith Edwards for revision of the English.

The article processing charges for this open-access publication
were covered by the Max Planck Society.

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Table 1. Sampling and analysis design. Sampled sites and their abbreviations are used throughout the paper. Number of sampled cryoconite holes for different analyses.

Site	Abbreviation	sample size	repeated sampling (4x)	Nutrients
Ebbabreen	E	6	–	–
Hørbyebreen	HC	16	5	3
Nordenskiöldbreen				
main site	NC	10	5	4
Retrettøya	NR	6	–	1
supraglacial lake	NL	6	–	–
Plateau	NI	6	–	1

Abbreviation: abbreviation for the sampling site, used in the text; sample size: number of sampled cryoconite holes; repeated sampling (4×): number of cryoconite holes that were sampled 4 times over the season; nutrients: number of cryoconite holes, where nutrient analysis were performed.

Table 2. Statistically significant (corrected $p < 0.05$) differences between the sites in their community structures (ANOSIM results) and environments (ANOVA results).

	HC	NC	NI	NL	NR
community					
E	A	G	G	G	A
HC		A	A	A,G	A
NC			A	–	A
NI				–	A
NL					A
environment					
E	De	Om	–	–	–
HC		Om	–	Sm	–
NC			De	Sm,Wc,Om,De	–
NI				Om	De
NL					–

A: Microalgae, G: Grazer
De: Depth, Om: Organic matter, Sm: Sediment mass, Wa: water content.

Table 3. Environmental variables for each site as ranges or averages ± the standard error. Bold numbers indicate particularly high values and italic numbers low values. *n* indicates the samples size for the different kind of analysis. Abbreviations for the different parameters are given in brackets.

Site		HC	NC	NI	NR	E	NL
n		16	10	6	5	6	6
Elevation (*e*)	m a.s.l.	170–230	150	200	20–50	160–525	200
Sediment load (sedmass)	mg w.w. cm^{-2}	238 ± 15	**277** ± 23	195 ± 27	**396** ± 162	212 ± 18	*161* ± 15
Water content (water)	M [%]	48 ± 2	51 ± 4	50 ± 5	47 ± 2	51 ± 3	*39* ± 6
Organic matter (om)	mg kg^{-1}	434 ± 14	**1184** ± 498	607 ± 83	603 ± 62	293 ± 81	*207* ± 134
Water depth (depth)	cm	*0.4–14.5*	0.1–28	**15.8–49**	1.7–33	8–43	8–43
Distance to deglaciated land	m	20–400	850	2800	*50–150*	50–1400	**3300**
Sediment coverage (sediment)	A [%]	**12.69** ± 0.53	8.79 ± 0.39				
Impact of birds (birds)	Rank	0–1	2	1	3	0–2	1
Particulate nutrients in sediments							
n		3	4	1	1		
Bioactive-PO$_4^{2-}$-P	mmol kg^{-1}	0.21 ± 0.02	0.15 ± 0.02	0.19 ± NA	0.20 ± NA		
Total P (TP)	mmol kg^{-1}	**6.81** ± 0.43	6.11 ± 0.86	4.88 ± NA	5.46 ± NA		
NH$_x$-N	mmol kg^{-1}	90.31 ± 12.38	77.46 ± 21.43	89.76 ± NA	**110.36** ± NA		
NH$_x$-N/TP		13.56 ± 2.47	14.56 ± 4.56	**18.40** ± NA	**20.20** ± NA		
PO$_4$-P/TP		0.03 ± 0.00	0.03 ± 0.01	0.04 ± NA	0.04 ± NA		
Dissolved carbon in water							
n		1	5				
Total organic carbon (TOC)	ppb	**4287** ± 45	2420 ± 238				
Inorganic carbon (TIC)	ppb	622 ± 2	**946** ± 262				
Total carbon (TOC + TIC)	ppb	4907 ± 45	3365 ± 122				

Table 4. Correlation table with Pearson's r^2 values and corrected p values between microalgae and invertebrate grazers. Significant values are marked in bold.

		Tardigrada	Rotifera
Chlorococcales	r^2	0.141	0.232
	p	0.471	0.075
Zygnemales	r^2	**0.3118**	**0.2885**
	p	**0.0171**	**0.0196**
Oscillatoriales	r^2	−0.044	−0.063
	p	0.796	0.796
Nostocales	r^2	0.044	−0.108
	p	0.796	1.00

Table 5. Regression table for linear regression models with median and mean sizes of microalgae as dependent variables and grazer densities as explanatory variables.

		Rotifera	Tardigrada	Ciliates
Nostocales colony size	*p*	0.9622	0.9622	0.9622
	Estimate	0.005	−0.001	0.002
Oscillatoriales length	*p*	**0.0083**	0.9622	**0.0149**
	Estimate	**−0.016**	0.0004	**0.0136**
Chlorococcales diameter	*p*	0.6072	0.9622	0.9622
	Estimate	−0.011	0.0004	−0.005
Zygnemales length	*p*	0.1032	0.9622	0.6072
	Estimate	−0.0158	−0.0001	0.0093

Table 6. Results for an RDA with spatial and temporal variables as explanatory factors and the explained variability of each variable on the final model. The glacier variable represents the three sampled glaciers.

	explained variability %	*F*	*p*
Glacier	58.6	5.2	0.003
place on glacier	55.8	4.9	0.008
time of sampling	37.3	3.2	0.015

Table 7. Results for the partial RDA with glacier and place as co-variables, after interactive-forward-selection-covariates. 14 environmental (physical, morphological and chemical) variables are tested, only significant results are shown. Explained variability means proportion of variability explained by each variable in the total model (variability explained by all variables is 64.3 % including non-significant ones). Contribution to explained variability means the proportion of a selected variable in variability explained by selected variables.

Name	Explained variability %	Contribution to explained variability %	pseudo-*F*	*p*
Birds	17.5	27.3	7.7	0.001
Elevation	14.1	21.9	7.2	0.009
Sediment load	10.5	16.4	6.2	0.023

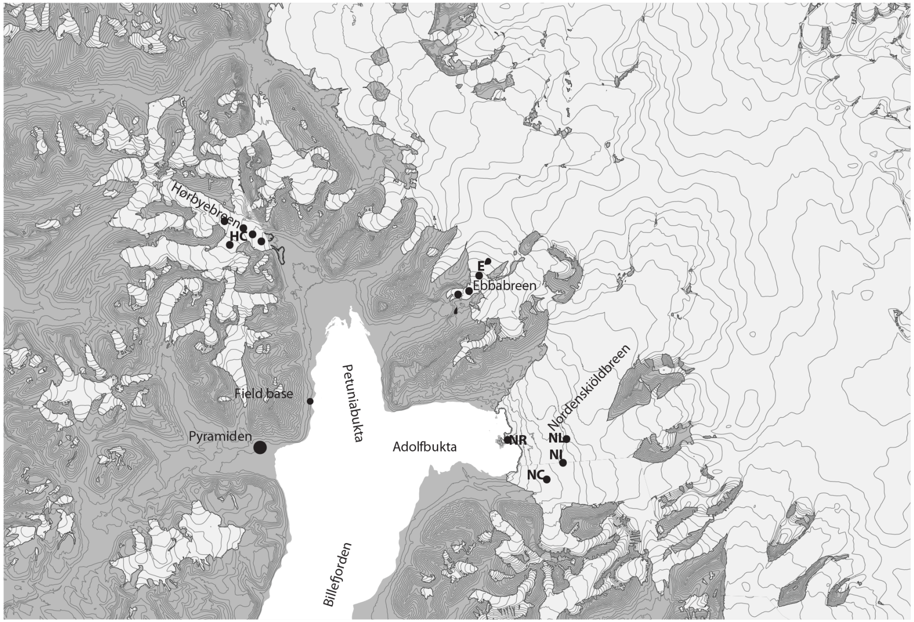

Figure 1. Sampling sites of the cryoconites. The abbreviations used are: HC for Hørbyebreen, E for Ebbabreen, NC for the main site on Nordenskiöldbreen, NI for the plateau on Nordenskiöldbreen, NL for the supraglacial lake on Nordenskiöldbreen, and NR for the part of Nordenskiöldbreen next to Retrettøya. The map is modified from the geographic data of the Norwegian Polar Institute (2014).

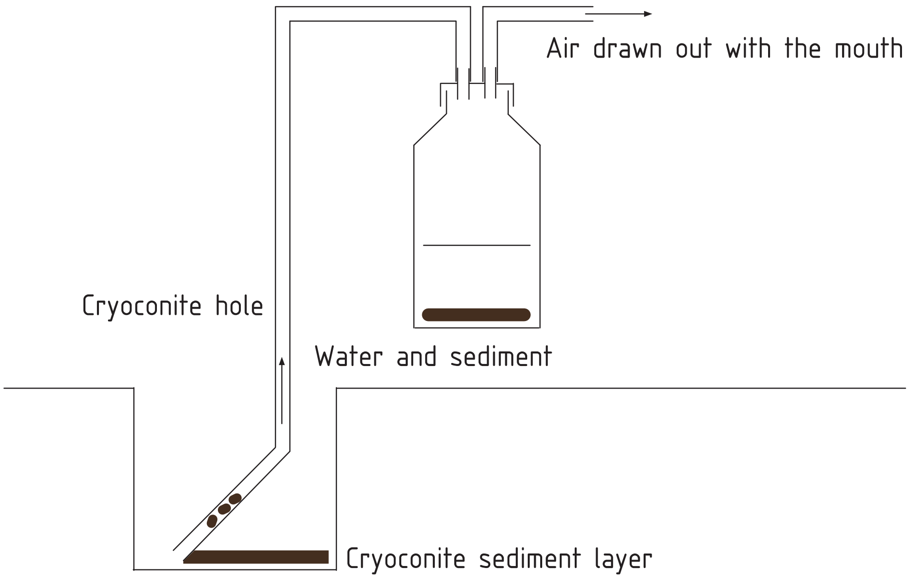

Figure 2. Sampling procedure for the sediment collection in cryoconite holes. An underpressure is produced by suction with the mouth. The underpressure is then refilled with the cryoconite sediment via a second tube. In order to avoid contamination, the two different tubes were labelled in different colors.

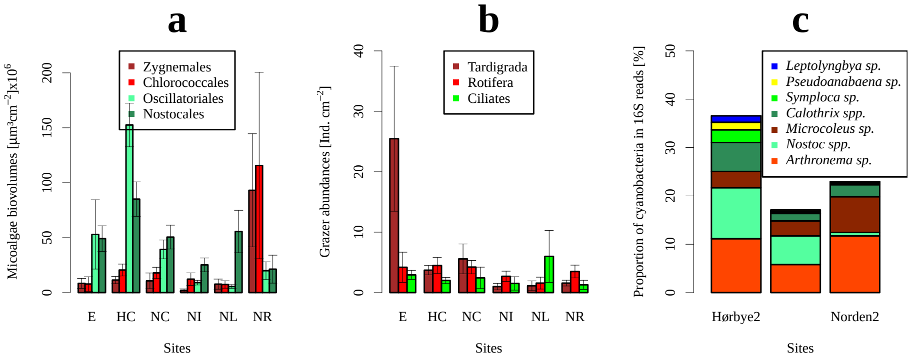

Figure 3. Mean densities in cryoconite sediment layers of microalgae **(a)** in ($10^{-6}\,\mu\text{m}^3\,\text{cm}^{-2}$) and grazer **(b)** in individuals cm^{-2} for the different sites (E: Ebbabreen, HC: Hørbyebreen, NC: Nordenskiöldbreen, NI: Nordenskiöldbreen plateau, NL: supraglacial pond on Nordenskiöldbreen, NR: Retrettøya). The error bars indicate the standard errors. **(c)** shows the proportion of different cyanobacterial genera within all 16S sequences from 2012 on Hørbyebreen (Hørbye.1) and Nordenskiöldbreen (Norden.1, Norden.2).

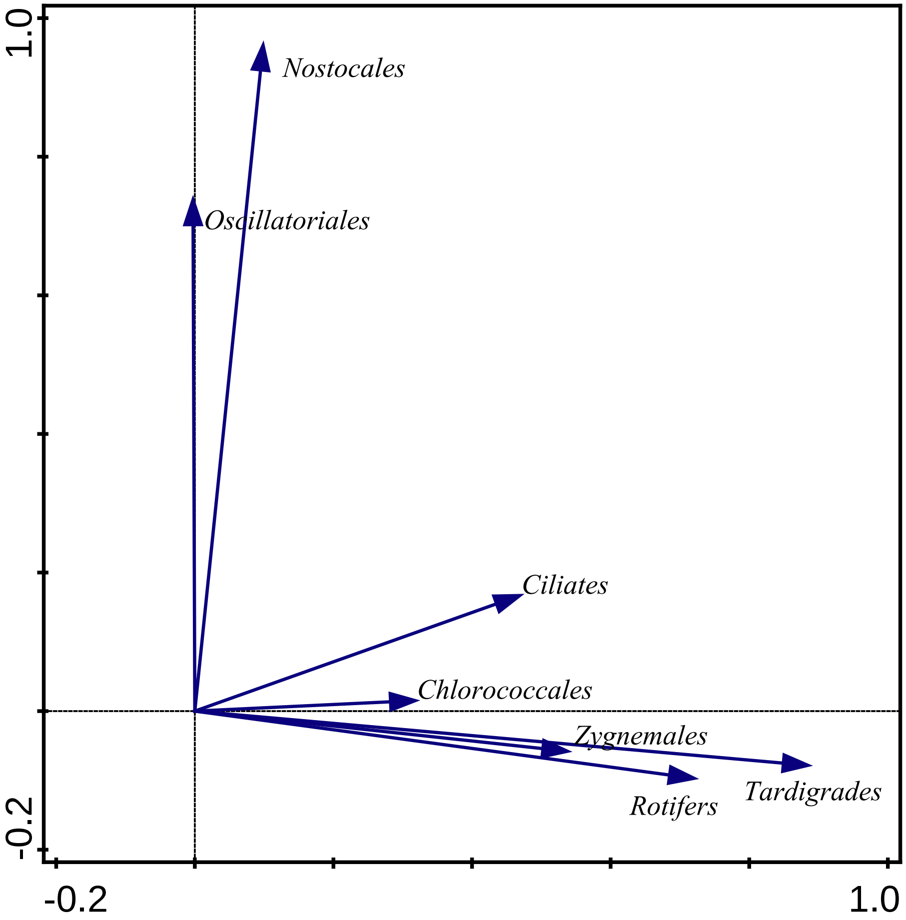

Figure 4. PCA biplot of all organisms collected in this study. Euclidean dissimilarities were used. The data are log transformed and microalgal biovolumes were standardized by multiplication by 10^{-6}.

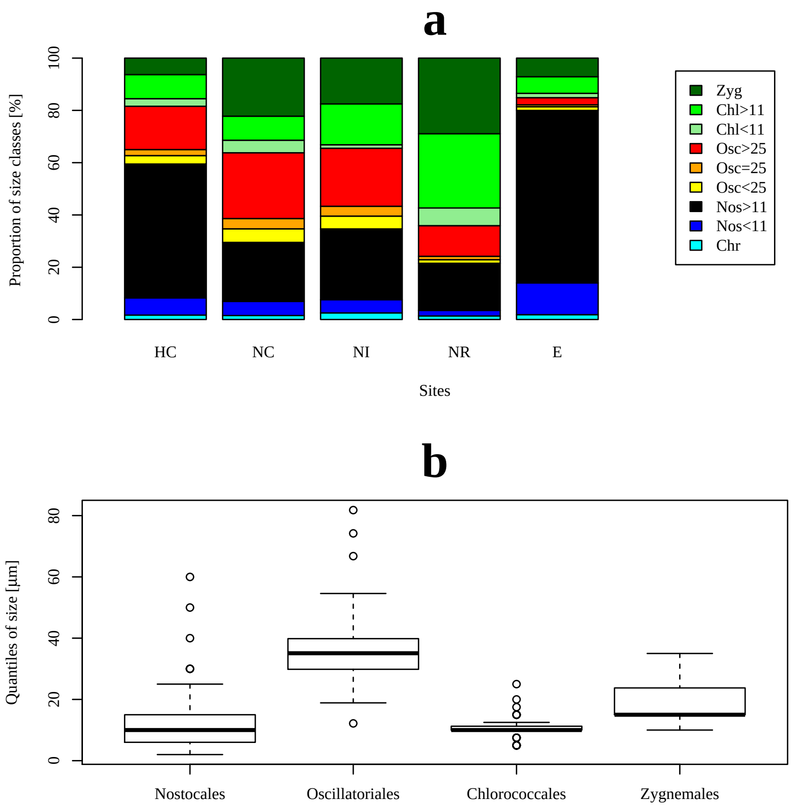

Figure 5. (a) Median, and quantiles of the biovolume proportion of suggested size classes and **(b)** the cell number proportion of the median length (Zygnemales), diameter (Chlorococcales), colony size (Nostocales), and mean length (Oscillatoriales) as smaller (<) or bigger (>) than a certain threshold in µm. The abbreviations used in plot a refer to Chroococcales (may include single cell Nostocales) (Chr), Nostocales (Nos), Oscillatoriales (Osc), Chlorococcales (Chl), and Zygnemales (Zyg).

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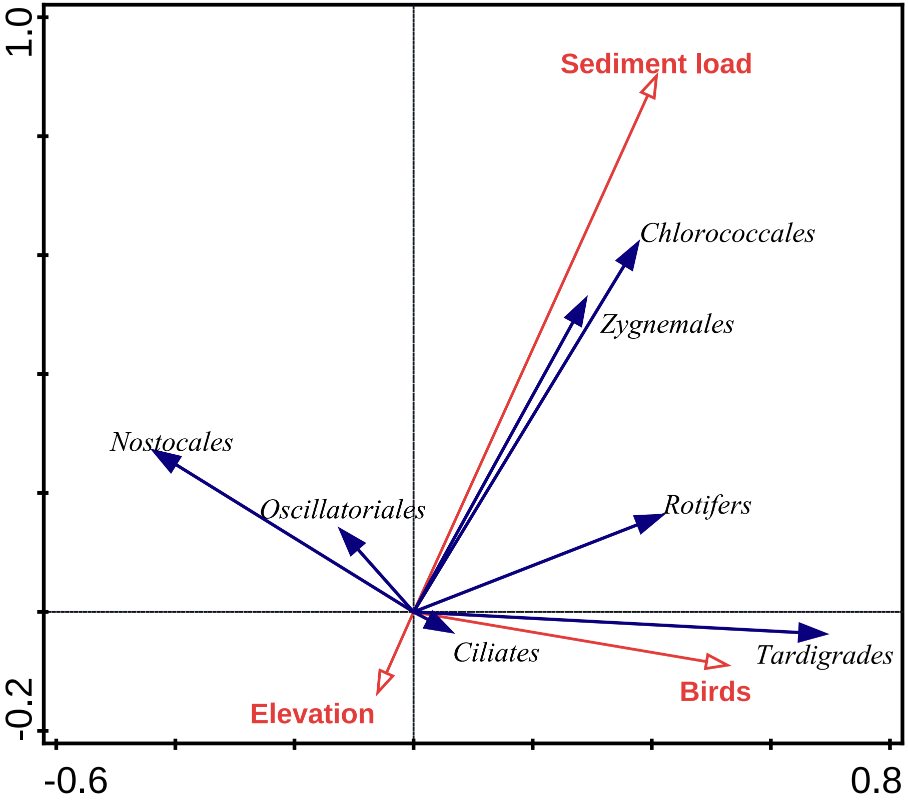

Figure 6. Biplot for the partial RDA with glacier and place as co-variables, after interactive-forward-selection-covariates. Rotifers were separated in bdelloid rotifers (Rotifers) and the monogonont *Encentrum* sp.