



Cyanobacterial and algal diversity in the vicinity of two different seabird colonies in Spitsbergen

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Abstract: The aim of the study was to compare cyanobacterial and algal assemblages occurring in ornithocrophilous habitats formed under the influence of two seabird colonies (mixed colony of piscivorous *Uria lomvia* and *Rissa tridactyla* and planktivorous *Alle alle*) nesting on the southwest side of Hornsund (Spitsbergen). Various influences of the bird colonies (e.g. surface trophy, treading) lead to the formation of ornithogenic habitats with quantitatively and qualitatively diverse cyanobacterial and algal assemblages. Only 6 species common to both habitats were identified, but due to their different proportions the similarity ended there. Cyanobacterial and algal assemblages of both ornithogenic habitats also react rather differently to the intensity of the bird colonies' influence. The assemblages located directly beneath piscivorous bird nests were characterized by a larger number of species, which decreased the farther from the colony it was. Cyanobacterial and algal assemblages located directly next to planktivorous bird nests were species poor, but species richness increased at locations farther from their direct influence. The obtained results confirmed that bird colonies characterized by different diet and behavior influenced the formation of two separate, quantitatively and qualitatively different cyanobacterial and algal assemblages. Species such as *Eucapsis* sp., *Gleocapsopsis* sp., *Gloeotheca* sp., *Woronichinia* sp., *Hematococcus* sp. were characteristic for algae and cyanobacteria assemblages in the vicinity of piscivorous bird colonies, whereas *Aphanocapsa* sp., *Gloeotheca* sp., *Komvophoron minutum*, *Pseudanabaena* sp., *Gleocystis* sp. 2 occurred in the vicinity of planktivorous bird colonies.

Key words: Arctic, Spitsbergen, cyanobacterial and algal assemblages, influence of seabirds, trophy.

Introduction

Some aspects of polar research are focused on vegetation (vascular plant communities; mosses, cyanobacterial and algal assemblages) formed as a result of nesting bird colonies enriching these ecosystems in nutrients (Stempniewicz *et al.* 2006, 2007; Smykla *et al.* 2007; Zmudczyńska *et al.* 2012). Polar habitats are characterized by a deficiency of nutrients such as nitrogen, potassium and calcium (Lindeboom 1984; Odasz 1994; Stempniewicz 2005) and, consequently, every change in nutrient level visibly influences the vegetation.

Birds obtaining nutrients as food from the sea introduce them into the ecosystem, leaving food remains, feathers and eggs, and depositing large amounts of guano near the colonies (Stempniewicz 1990; Godzik 1991; Stempniewicz and Węśławski 1992; Anderson and Polis 1999; Tatur 2002; Lięza and Smal 2003; Hawke and Newman 2004; Breuning-Madsen *et al.* 2008; Mulder *et al.* 2011; Zwolicki *et al.* 2013). The quantity of nutrients introduced by bird colonies into polar ecosystems low in nutrients is higher than from other sources, such as precipitation, sea spray or nitrogen assimilated from heterocytous cyanobacteria (Erskine *et al.* 1998; Bokhorst *et al.* 2007; Skrzypek *et al.* 2015). Decomposition by soil microorganisms releases nutrients into circulation, and they may be assimilated by producers (Ryan and Watkins 1989; Cragg and Bardgett 2001; Hodkinson *et al.* 2002; Smith and Froneman 2008). Habitats formed in this way and rich in nutrients provide conditions for the growth of eutrophic vegetation but may also limit the development of species which prefer less rich habitats. Depending on requirements, tolerance and adaptation capabilities, species richness and plant community coverage (including cyanobacterial and algal assemblages) change (Theodose and Bowman 1997; Pennings *et al.* 2005; Zelenskaya and Khoreva 2006; Smykla *et al.* 2007). That way ornithocoprophilous habitats characterized by particular cyanobacterial and algal assemblages, mosses and vascular plant communities form in the range of nesting birds (Hogg and Morton 1983; Myrcha and Tatur 1991; Elvebakk 1994; Matuła *et al.* 2007; Jakubas *et al.* 2008; Richter *et al.* 2009, 2014, 2015; Zwolicki *et al.* 2015).

In the Svalbard region, on the Hornsund Fiord, there are two big bird colonies. On the coastal Gnålberget cliff there is a mixed colony of two piscivorous bird species – Brünnisch's guillemot (*Uria lomvia* L.) and black-legged kittiwake (*Rissa tridactyla* L.). On the Ariekammen slope, further from the coast, there is a colony of planktivorous little auk (*Alle alle* L.). Their diet and behavior influence the ornithocoprophilous habitats forming nearby. They are shaped by the direct influence of birds (treading) and nutrients (their quantity and quality) provided by birds through guano and food remains. Among them, nitrogen and phosphorus are the most significant for the diversity of habitats as to their trophy. The excrement of piscivorous *Uria lomvia* and *Rissa tridactyla* are rich

in phosphorus as a result of this element's high content in fish bones. Studies conducted in the area confirmed that, consequently, there is a high content of phosphorus in the soil in the direct vicinity of the colonies. On the other hand, around the colony of the planktivorous *Alle alle* there was a high content of nitrate nitrogen (Zwolnicki 2013; Ziótek and Melke 2014).

Therefore, we may assume that two separate ornithogenic habitats will develop under the influence of two seabird colonies with different diet and behaviour. Since the most common and sometimes only components of polar tundra are cyanobacteria and algae, and since they are communities with the quickest reaction to changes in soil trophicity (Davey and Rothery 1992; Kaštovska *et al.* 2005; Lan *et al.* 2013), the aim of the research was to compare two cyanobacterial and algal assemblages occurring in ornithocrophilous habitats formed under the influence of piscivorous and planktivorous seabird colonies.

Study area

The research was carried out at the foot of the Gnålberget cliff of Hornsund area and on the Arie kammen mountain slope (West Spitsbergen, Svalbard Archipelago). The locations chosen for the study were situated in ornithocrophilous habitats, characterized by long periods of dryness and strong sun exposure in summer. Within the soil habitats 10 sites were nominated for phycological research (Fig. 1).

The area with sites 1–5 was located at the foot of the Gnålberget rocky cliff (Fig. 2A) and was under the influence of mixed nesting colonies of two piscivorous seabird species – guillemots (*Uria lomvia*) and black-legged kittiwake (*Rissa tridactyla*) – located at the altitude of 500–400 m, with slope inclination of 45–50° (77°02' N, 015°91' E).

Sites 1–2 were located directly under a seabird colony. The soil was highly dried, covered with the crumbled remains of plant material from birds' nests, without vascular plants and with only *Prasiola crispa* thalli.

Sites 3–5 were located slightly lower than the previous ones and were under lesser influence of the colonies. The soil was covered with a *Cochlearia groenlandica* – *Poa alpina* community, macroscopic *Prasiola crispa* thalli and cyanobacteria crusts.

The area with sites 6–10 was located on Arie kammen slope (Fig. 2B), under the influence of planktivorous seabird colonies of little auks (*Alle alle*), located at the altitude of 200–100 m, slope inclination 35–40° (latitude 77°00'36.8"–77°00'35.9" N, longitude 015°31'2"–015°31'7" E).

Sites 6–8 were located directly next to the colony. The surface was dried out, trodden by birds, covered with guano, food remains and feathers. The

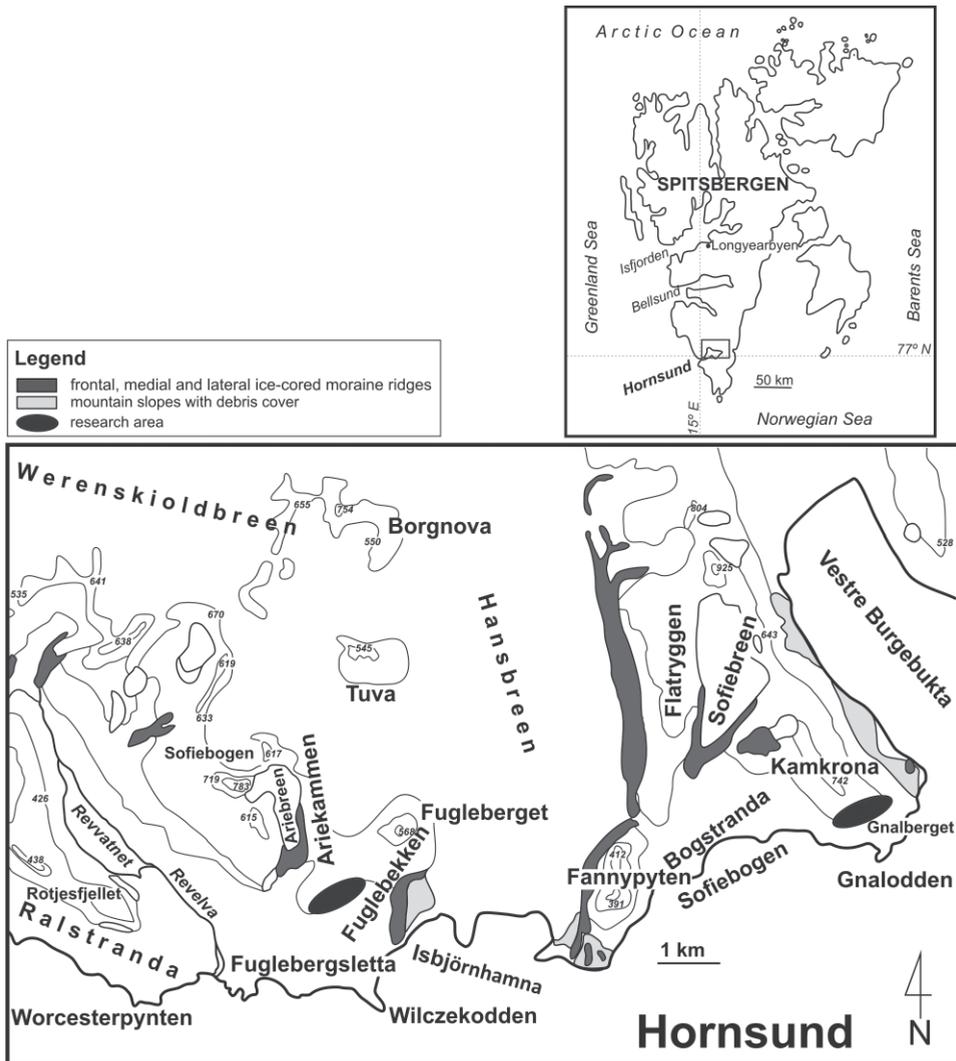


Fig. 1. A. Location of the Hornsund fjord; B. Location of the sites from where the samples were taken; black ovals show the ornithocrophilous habitats.

soil was covered with a *Prasiola crisper* community and a small proportion of mosses (mainly as dead remains).

Sites 9–10 were located farther from the bird colony. They had a dry surface with visibly diverse vegetation, particularly *Chryso-splenium tetrandrum* – *Cochlearia groenlandica* communities and clumps of mosses with *Poa alpina* var. *vivipara*, *Cerastium arcticum*, *Salix polaris* and small thalli of *Prasiola crisper*.

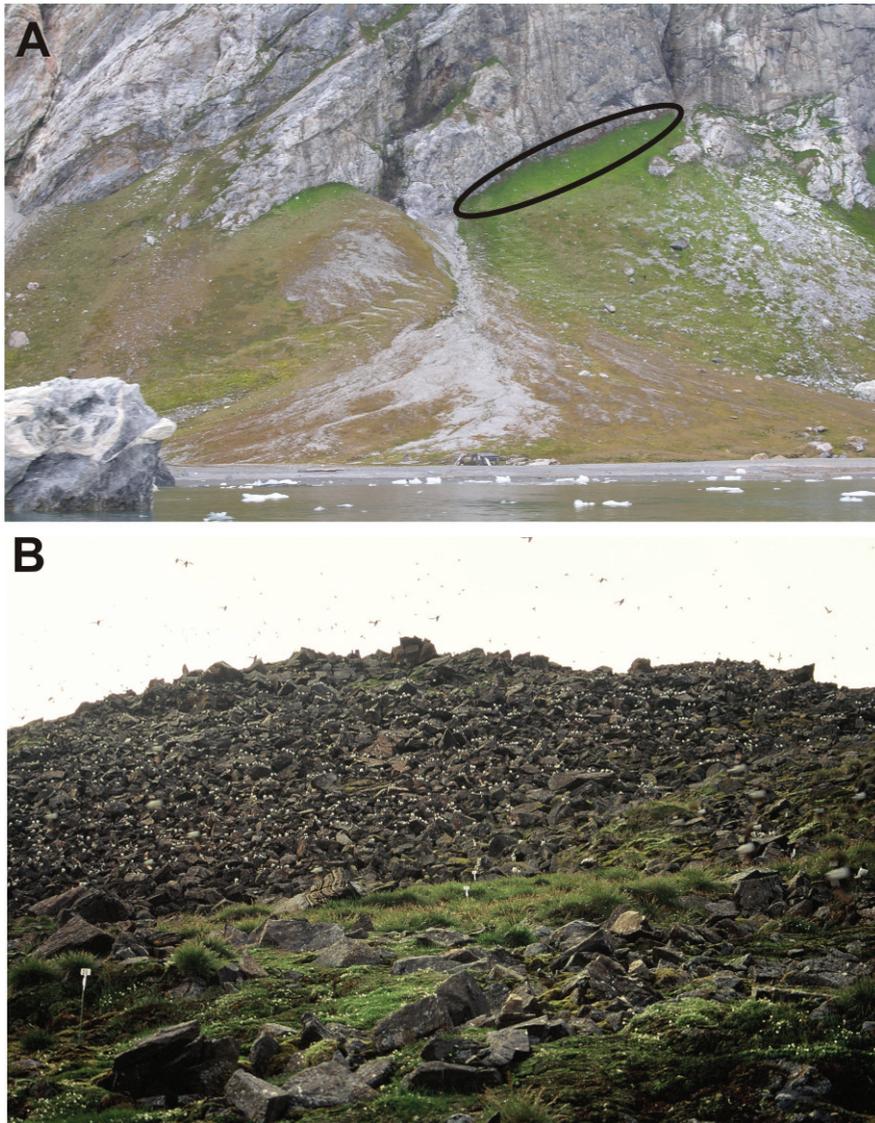


Fig 2. Study area: A. Gnålberget rocky cliff, B. Ariekammen slope.

Materials and methods

Research was conducted during the Arctic summer in July and August in the years 2009–2013. Samples were collected from soil surface and dead plant remains, between the moss turf mosaic and vascular plants, from a surface of 20 cm² from all habitats in four repetitions.

Species observations were conducted with a Nikon Eclipse TE2000-S light digital microscope. The taxon was digitally archived using the NIS image analysis program, which enables one to save the images with the proper scale of objects. The identification was performed live and also on material preserved. The abundance of particular species was estimated on a 5-degree scale (Table 1). Taxonomic classification was done according to Hoek *et al.* (1995). The names of species were updated according to detailed literature on the species (Komárek 2016).

The statistical analyses were performed using the following programs: MVSP 3.1 (Kovach 1985–1999), CANOCO 4.5 (Braak, Šmilauer 2002) and STATISTICA v. 12 package (StatSoft Inc. 2014). Shannon's diversity index (Shannon and Weaver 1949) was used to describe species diversity and evenness. In order to estimate the similarity of habitats with regard to phycoflora diversity we used numerical analysis including hierarchical-accumulative classification. In order to estimate the degree of phycoflora similarity between the habitats, Cosine Theta analysis was used. In order to arrange the samples according to their species composition, the ordination method was used. The calculated gradient of analyzed data was over 2 SD, which confirms the presence of unimodal data, hence the use of detrended correspondence analysis (DCA).

Results

Taxonomic characteristics of cyanobacterial and algal assemblages in the research areas. — A total of 55 cyanobacterial and algal species were identified in the studied area; 31 species occurred in habitats located on the Gnålberget cliff (14 coccoid or colonial cyanobacteria, 11 filaments without heterocytes, 1 heterocytous type and 5 species of Chlorophyta) and 28 species on the Arie kammen slope (5 coccoid or colonial cyanobacteria, 14 filaments without heterocytes, 1 heterocytous type and 8 species of Chlorophyta). The quantity and species composition of particular cyanobacterial and algal groups, as well as the quantity of particular species in the habitat, differed significantly in the studied ornithocrophilous habitat types (Table 1).

At the foot of the Gnålberget cliff, in a location under the influence of piscivorous birds, the highest number of species was found at sites 1–2 (24 species, of which half were coccoid cyanobacteria). The dominating species was *Prasiola crispa*, which formed crusty thalli covering up to 50% of the studied area's soil. It was numerously accompanied by the following cyanobacteria: *Phormidium autumnale*, *Pseudanabaena frigida*, *Merismopedia* sp., *Gleocapsopsis* sp., *Eucapsis* sp. and *Cyanosarcina* sp. Other species occurred in small quantities but were significant for the character of the habitat's phycoflora (*Coccomyxa* sp., *Gloeocapsa punctata*, *Oscillatoria tenuis*, *Synechocystis* sp.).

At sites 3–5, further away from the colony, the study revealed a larger proportion (75%) of *P. crisper* in an assemblage which formed monostromatic green thalli. In the case of *Phormidium autumnale* there was also a larger proportion in the assemblage. The phycoflora was also characterized by the occurrence of species such as *Gloeocapsopsis* sp., *Merismopedia* sp., *Pseudanabaena* cf. *minima*, *Pseudanabaena* cf. *mucicola*, *Leptolyngbya foveolarum*, *Woronichinia* sp., *Chloorococcus helveticus*, *Ch. varius*, *Phormidium* sp. 1, *P. uncinatum*.

The analyses of phycoflora in the locations under the influence of planktivorous bird colonies also revealed the dominance of *Prasiola crisper*. At sites 6–8 (located within the bird colonies' influence) it covered 100% of the surface. It formed macroscopic, green cracked thalli. Cyanobacterial and algal assemblages were not rich in species and only had 3–5 taxa (*Aphanocapsa* sp., *Merismopedia* sp., *Komvophoron minutum*, *Phormidium autumnale*, *Prasiola crisper*).

At sites 9–10 there was a rapid growth in the quantity of species (17–20), particularly with regard to filamentous cyanobacteria (7–8 taxa), mostly of *Leptolyngbya*, *Phormidium*, *Oscillatoria* genera. These habitats were also distinguished by the presence of such cyanobacteria as *Gloeocystis* sp. 2, *Scotielopsis oocystiformis*, *Tetracystis* sp., and *Trochiscia granulata*.

Diversity and evenness characteristics of cyanobacterial and algal assemblages in the research areas. — At the sites located on the Gnålberget cliff the Shannon-Weaver diversity index (H') was 1.084. The high value of the biodiversity index results, above all, from the evenness of proportions of the occurring species. This is also confirmed by the high value of the evenness index (J) – 0.963 – suggesting that despite the quantitative dominance of *Prasiola crisper*, all species influence the shaping of assemblages in habitats under the influence of piscivorous birds (*Uria lomvia*, *Rissa tridactyla*).

At the sites located on the Arikammen slope the diversity and evenness indices have much lower values. In habitats under the influence of planktivorous bird colonies (*Alle alle*) they are respectively 0.33 (H) and 0.36 (J). It is a result of the clear dominance of *Prasiola crisper* in the assemblages, which, in places in the direct vicinity of the bird colonies, covers up to 100% of the surface. The role of the other species is marginal.

Similarity between research areas – hierarchical-accumulative classification. — In order to determine the similarities between the habitats regarding the occurring species a numeric hierarchical-accumulative classification was conducted.

The dendrogram showing the similarities between sites (Fig. 3) has two visible clusters. The first cluster groups habitats 1–5 located on the Gnålberget cliff and site 10 located on the Arikammen slope. The greatest similarities are found

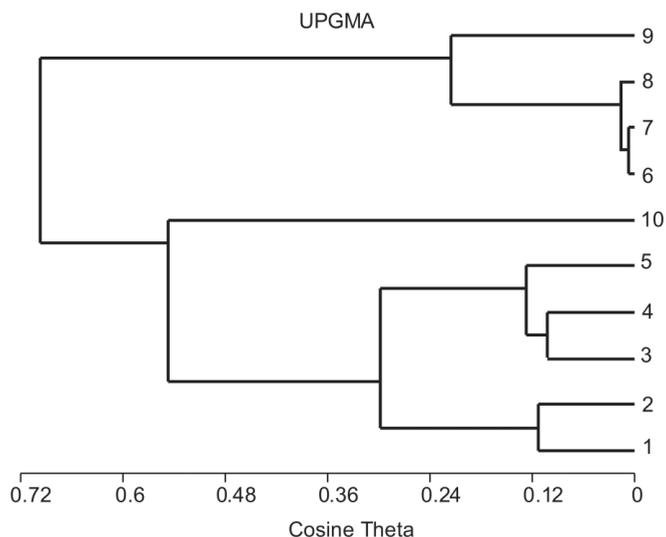


Fig 3. Hierarchical cluster Cosine Theta analysis based on the similarity of cyanobacterial and algal assemblages on the research sites (1–10).

between sites 1 and 2, which are characterized by the highest species diversity of all analyzed sites, especially with regard to coccoid cyanobacteria. Sites 3–5 had lower diversity and were dominated by *Prasiola crispa* and *Phormidium autumnale*.

Site 10 represented a slightly different phycoflora. It was located within the range of the planktivorous bird colony. However, its similarity to the group of sites under the influence of the piscivorous bird colony was determined by a similar proportion of *P. autumnale* and *P. crispa* in the assemblages.

The second cluster includes sites 6–9 located on the Ariekammen slope. The greatest similarity is found among sites 6–8, located the closest to the *Alle alle* colony and covered almost entirely with thalli of a single species, *Prasiola crispa*. Site 9 is less similar because the *P. crispa* proportion is significantly lower and the number of species forming the assemblage is considerably higher.

Relationship between research areas – detrended correspondence analysis. — In order to obtain information about the mutual relations between the studied sites and the related species, detrended correspondence analysis (DCA) was conducted (Fig. 4). The generated ordination diagram shows the diversity of species occurrence in relation to habitats along the gradients represented by two ordination axes. Together they constitute 53% of total diversity, where the first axis shows 35% of diversity and the second one in terms of trophic 18%. In the ordination space there are clear separate groups of cyanobacterial and algal

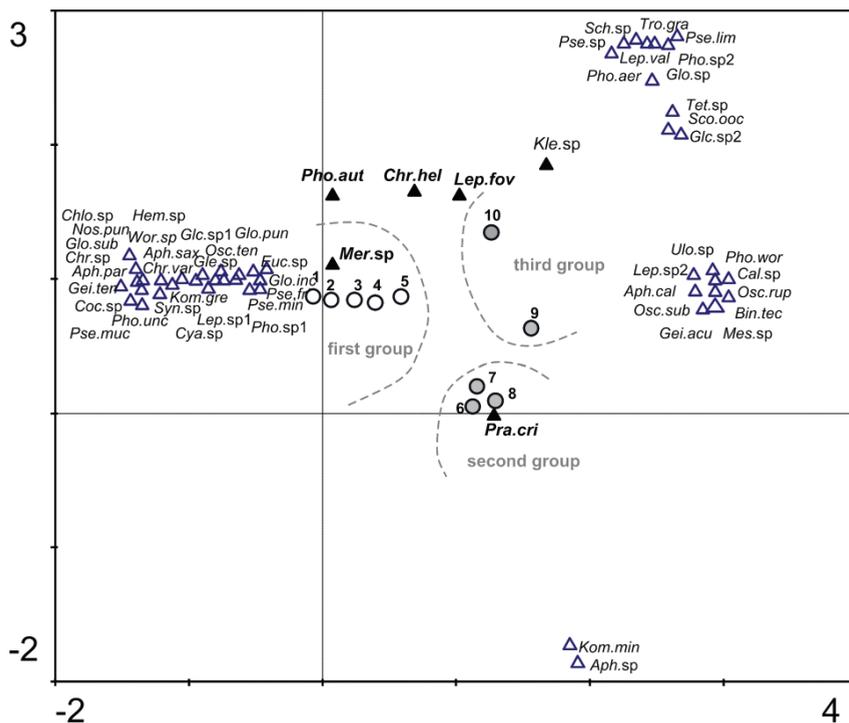


Fig 4. The results of DCA analysis; ordination diagram shows the diversity of species occurrence in relation to habitat. Black triangles show species common for all habitats, white triangles show species occurring on research sites, white circles show sites located at the foot of the Gnålberget cliff, grey circles show sites located on Arieckammen slope.

assemblages representing two types of habitats with different habitat conditions associated with the differences in the birds' diets and behavior.

The first group comprises sites located at the foot of the Gnålberget cliff (sites 1–5). Their similarity was caused by the highest species diversity of all the studied sites. *Prasiola crispera*, *Phormidium autumnale* and *Merismopedia sp.* had the greatest influence on the formation of the assemblages in this group. The similarity between the sites is confirmed by quantitative data (Table 1) showing that these species were the most numerous constituents of the flora. They also show an increase in the population of the species with increasing distance from the intense bird colony influence. *Pseudanabaena frigida*, *Pseudanabaena minima*, *Gloeotheca cf. incerta*, *Merismopedia sp.*, *Gleocapsopsis sp.*, *Phormidium sp. 1* and *Eucapsis sp.* also have a significant role in the shaping of the assemblages. These species reached a higher quantity and play a dominant role in the assemblages. Other species, despite a lower proportion in the assemblages, are responsible for the distinctiveness of these habitats.

The second group comprises sites 6–8 located on the Arie-kammen slope, directly under the bird nests. At such sites the dominating *P. crisper* had the greatest influence on formation of cyanobacterial and algal assemblages. Quantitative data show a small proportion of other species – *Aphanocapsa* sp., *Merismopedia* sp., *Komvophoron minutum* and *P. autumnale*. Those habitats had the lowest species diversity.

The third group, sites 9–10, are also located on the Arie-kammen slope but under lesser influence of the planktivorous bird colonies. The group has a higher similarity to the first group, which is visible in the common species – *Klebsormidium* sp., *Leptolyngbya foveolarum* and *Chroococcus helveticus*. Quantitative data also confirm this group's (sites 9–10) similarity to the first group (1–5), because its assemblages had a similar proportion of *P. crisper* and *P. autumnale*. The distinctiveness of these sites is determined by species unique to them (e.g. *Aphanothece caldariorum*, *Calothrix* sp., *Geitlerinema acutissima*, *Leptolyngbya* sp. 2, *Oscillatoria* cf. *rupicola*, *O. subbrevis*, *Pseudanabaena limnetica*, *Pseudanabaena* sp. 2), which results in higher species diversity than in the second group.

The diagram clearly shows species common for all habitat groups. They were *Prasiola crisper*, *Phormidium autumnale* and *Merismopedia* sp.

Discussion

Cyanobacterial and algal ornithogenic assemblages in the Hornsund area (Spitsbergen) were formed under the influence of two seabird colonies with different diets. Nesting birds introduce nutrients to ecosystems low in nutrients, thus changing soil trophicity and habitat conditions (Stempniewicz *et al.* 2006; Smykla *et al.* 2007; Jakubas *et al.* 2008; Huang *et al.* 2014; Zwolnicki *et al.* 2015). This, in turn, causes changes in the quantity and mass of vascular plant communities and cyanobacterial and algal assemblages in the vicinity of nesting locations (Elvebakk 1994; Matuła *et al.* 2007; Zmudczyńska *et al.* 2009; Richter *et al.* 2009; Kolb *et al.* 2010; Ellis *et al.* 2011; Mulder *et al.* 2011; Richter *et al.* 2014, 2015a, b; Wojciechowska *et al.* 2015; Zmudczyńska-Skarbek *et al.* 2015a, b).

The conducted analyses have shown that both bird colonies nesting in the Hornsund area and differing in diet and behavior (Jakubas *et al.* 2008) influenced the formation of two habitat types characterized by different cyanobacterial and algal assemblages. At all sites located on the Gnålberget cliff, which is under the influence of *Uria lomvia* and *Rissa tridactyla* (piscivorous seabirds), cyanobacterial and algal assemblages had high species richness. Such rich phycoflora was a result of higher humidity than in the sites within the *Alle alle* (planktivorous seabird) colony, no direct treading by birds and a very high level of phosphorus in

the soil (Zwolicki *et al.* 2013). Phosphorus is an element essential for vegetation because of its role in biochemical processes. Its deficiency in the environment is a factor limiting primary production and increased P availability may lead to greater species diversity (Smil 2000; Elster *et al.* 2007; Madan *et al.* 2007).

The habitats located the closest to piscivorous seabirds colonies, where phosphorus reached a very high concentration (Zwolicki *et al.* 2013), were richer in filamentous and coccoid cyanobacteria and green algae. *Pseudanabaena frigida*, which has a broad spectrum of occurrence in terms of trophic levels and humidity, but prefers locations with higher nutrient values, had a particularly large proportion in the assemblage. The diversity of assemblages in these habitats was to a large extent influenced by numerous Synechococcales species. Earlier research from polar regions has shown that it is morphologically a very diverse group. Its representatives increase the biodiversity of Arctic tundra by colonizing ecological niches (Komárek 2013, 2014; Gama *et al.* 2014). These habitats also differed due to the presence of coccal green algae such as *Gloeocystis* sp. 1, *Coccomyxa* sp., and *Chlorella* sp. Species of these genera also occurred in an Antarctic area under the influence of Adélie penguin colonies (Cavacini 2001). Therefore, it may be assumed that habitats formed under the influence of piscivorous bird colonies are suitable for them.

The characteristics of the habitats located at the foot of the Gnålberget cliff also influenced the quantitative proportion and size of thalli of two species significant for eutrophic habitats – *Prasiola crispa* and *Phormidium autumnale*. Both *P. crispa* and *P. autumnale* increased their proportion in the habitat in the direction of places more distant to *Uria lomvia* and *Rissa tridactyla* colonies. *Phormidium autumnale* is a species with a wide spectrum of occurrence in polar regions (Komárek *et al.* 2008; Strunecký *et al.* 2010) and prefers sites with higher nitrogen concentrations but does not occur in sites with high phosphorus concentrations (Heath *et al.* 2014; Brasell *et al.* 2015). Similarly, *Prasiola crispa* is a typical species in cold-temperate regions, where it is usually associated with habitats rich in organic nitrogen (Graeve *et al.* 2002; Holzinger *et al.* 2006; Matuła *et al.* 2007; Richter *et al.* 2009; Broady *et al.* 2012; Richter *et al.* 2014, 2015).

Planktivorous bird colonies (*Alle alle*) influenced the formation of ornithogenic habitats with different habitat conditions both in trophic and the intensity of bird influence. This resulted in the formation of cyanobacterial and algal assemblages with different species compositions and different quantitative proportions of species. At sites located in the direct vicinity of the colony the assemblages were not rich. The intense interference of birds associated with their behaviour leads to the treading of places near the nests. Consequently, there is a habitat lacking mosses and vascular plants, which, in turn, exposes the soil to drying, freezing and thawing. In such conditions, lacking any competition

such as mosses or vascular plants, *Prasiola crispera* dominated, with a very small number of other species (3–5), forming large, widespread thalli covering almost 100% of the surface. The dominance of this species is connected with the characteristics of the habitat formed under a very specific diet of the nesting birds, which introduce large amounts of nitrogen to the soil. *P. crispera* is an indicator species for nitrophilous ecosystems (Pizzaro *et al.* 1996; Lud *et al.* 2001; Raven and Taylor 2003; Wojtuń *et al.* 2013; Szymański *et al.* 2013). The thalli of *Prasiola crispera* in the habitat had a monostromatic lamellar, cracked form, which is probably a result of unfavorable habitat conditions caused by constant treading by birds and the risk of drying out.

At sites distant from the planktivorous bird colonies habitat conditions changed due to the limited interference from birds and the emergence of vascular plants and mosses (*Chryso-splenium tetrandrum*–*Cochlearia groenlandica* communities) (Olech 1990). The increased proportion of *Phormidium autumnale* in the assemblage means that the humidity of the soil increased, creating optimal conditions for this species (Matuła *et al.* 2007; Richter *et al.* 2014, 2015). All these factors led to the formation of an assemblage rich in cyanobacteria and algae. The quantity of filamentous cyanobacteria and green algae not recorded at previous sites increased.

Cyanobacterial and algal assemblages of both studied ornithogenic habitats had a similar number of species but differed significantly in qualitative composition. The difference is confirmed by the presence of only six common species out of the 55 identified ones. The species recorded in both ornithogenic habitats are widespread and often recorded in polar regions (Elster *et al.* 2008; Komárek and Elster 2008; Komárek 2013, 2014).

Conclusions

The obtained results confirmed that both seabird colonies nesting in the Hornsund area, differing in diet and behavior, influence the different habitat conditions in the Arctic tundra. Cyanobacteria and algae in both ornithogenic habitats respond by forming assemblages differing in quantity and quality. It is associated with the particular preferences of individual species. The difference between the habitats is also visible in the small number of common species, which further distinguish the habitats with regard to the quantitative representation in the assemblages.

The cyanobacterial and algal assemblages of the studied habitats react differently to the intensity of the bird colonies' influence. The assemblages located directly under the piscivorous birds' nests were characterized by the highest number of species, which decreased the farther from the colony it was. Cyano-

bacterial and algal assemblages located in the direct vicinity of the planktivorous bird colonies were species poor, but the species richness increased at sites more distant from the colony's influence.

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