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Relationship of cyanobacterial and algal assemblages with vegetation in the high Arctic tundra (West Spitsbergen, Svalbard Archipelago)

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Abstract: The paper presents the results of a study of cyanobacteria and green algae assemblages occurring in various tundra types determined on the basis of mosses and vascular plants and habitat conditions. The research was carried out during summer in the years 2009–2013 on the north sea-coast of Hornsund fjord (West Spitsbergen, Svalbard Archipelago). 58 sites were studied in various tundra types differing in composition of vascular plants, mosses and in trophy and humidity. 141 cyanobacteria and green algae were noted in the research area in total. Cyanobacteria and green algae flora is a significant element of many tundra types and sometimes even dominate there. Despite its importance, it has not been hitherto taken into account in the description and classification of tundra. The aim of the present study was to demonstrate the legitimacy of using phycoflora in supplementing the descriptions of hitherto described tundra and distinguishing new tundra types. Numeric hierarchical-accumulative classification (MVSP 3.1 software) methods were used to analyze the cyanobacterial and algal assemblages and their co-relations with particular tundra types. The analysis determined dominant and distinctive species in the communities in concordance with ecologically diverse types of tundra. The results show the importance of these organisms in the composition of the vegetation of tundra types and their role in the ecosystems of this part of the Arctic.

Key words: Arctic, cyanobacteria, algae, community classification.

Introduction

Severe climate and habitat conditions in polar regions not only limit the colonization process but also determine the directions and the speed of succession of vegetation in these regions. On open surfaces, especially near the margins of glaciers, cyanobacteria, algae, fungi and mosses creating vast crusts, dominate in quantity, biomass and productivity of organic matter (Zielke *et al.* 2002; Hu and Liu 2003; Elster and Benson 2004; Kaštovská *et al.* 2005; Thomas *et al.* 2008; Pócs 2009).

In the Spitsbergen tundra these organisms are still relatively unknown, despite the fact that cyanobacteria and algae co-dominate in various tundra communities on large surfaces. Previous studies of Spitsbergen phycoflora were concentrated mainly on the diversity of the freshwater and terrestrial cyanobacteria and algae (Matuła 1982; Elster *et al.* 1994; Matuła *et al.* 2007; Kim *et al.* 2008, 2011; Richter *et al.* 2009; Komárek J. *et al.* 2012; Davydov 2014) and describing individual species (Kvíderová *et al.* 2011; Strunecký *et al.* 2012; Komárek J. and Kovacik 2013; Richter and Matuła 2013; Richter *et al.* 2014). There are, however, no complementary data characterizing phycoflora in connection with vascular vegetation and mosses in the area.

The description of algal and cyanobacterial assemblages in ecologically diverse types of tundra is the next step in understanding the role of these organisms in creating plant communities in the area. A detailed analysis of cyanobacterial and algal assemblages allowed us to determine the dominant and distinctive species for tundra types in the studied area.

This article is the first attempt to analyze and discuss the relevant relations (or lack thereof) at the level of associations between cyanobacteria, algae and vegetation.

Study area, material and methods

The research was carried out at the base and on the Ariekammen mountain slope (512 m), the Fuglebergsletta marine terrace and Fuglebekken catchment, reaching to the sea shore and the bay situated on the southwest side of Hornsund (West Spitsbergen, Svalbard Archipelago). The locations chosen for the study were situated in different types of tundra (18 types). Within the tundra, 58 sites were nominated for phycological research (Table 1, Figs 1–3).

Samples were collected during the Arctic summer in July and August in the years 2009–2013. Species observations were conducted with a Nikon Eclipse TE2000-S light digital microscope, equipped with a Nikon DS-Fi1 camera. Taxa were digitally archived using the NIS image analysis program, which enables to save the images with the proper scale of objects. The identification was performed live and also on material preserved with "etaform" (3:1 alcohol, formalin). The abundance of particular species was estimated on a scale of 1–10, where 1 means sporadic occurrence and 10 means 90–100% representation of the species in the assemblages.

In order to classify the results by qualitative and quantitative analyses of the species composition of cyanobacteria and green algae, we used numerical analysis including hierarchical-accumulative classification using the MVSP 3.1 software.

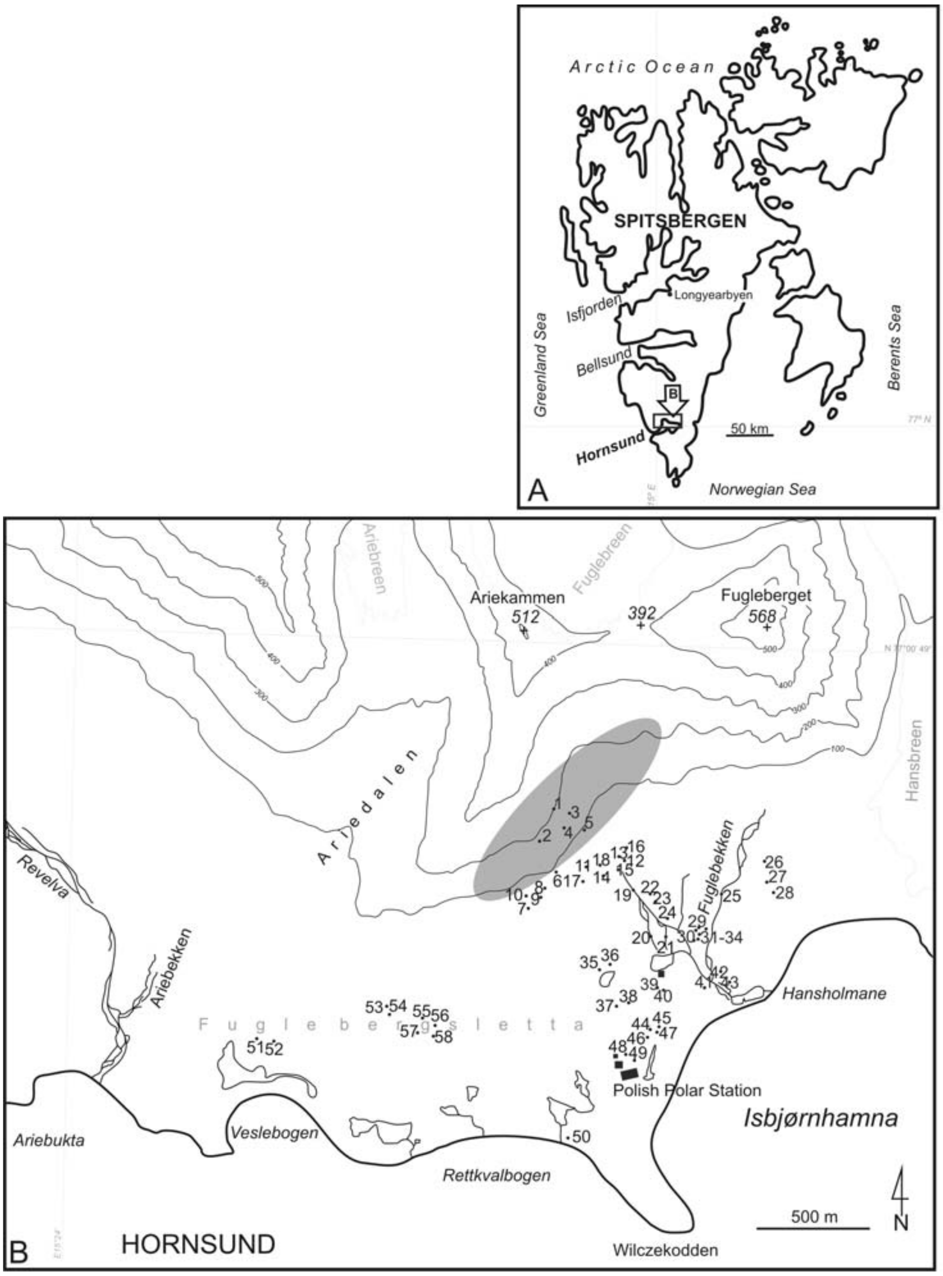


Fig. 1. **A**. Location of the Hornsund fjord. **B**. Fuglebekken catchment and Fuglebergsletta marine terrace. Gray: location of *Alle alle* colonies; 1–58: sampling points (detailed description in Table 1).

In order to estimate the degree of phycoflora similarity between the habitats, Cosine Theta Analysis was used. This analysis allows to obtain a classification dendrogram showing the hierarchy of similarities between the habitats (Figs 4, 5).

Table 1

Study area, types, location and characteristic of tundra.

Type of tundra (vegetations)	Sites		Characteristics of tundra	Trophy	Moisture	Vegetation	Latitude	Longitude
Ornito-coprophilous tundra with *Prasiola crispa*	1–3	Ariekammen slope	located 200 m high, inclination 35–40°, under strong influence of little auk (*Alle alle*); samples were collected from soil surface and dead plant remains	highly eutrophic	dry	*Prasiola crispa* community with a small share of *Plagiomnium ellipticum*, *Sanionia uncinata*, *Tetraplodon mnioides*, *Dicranum* sp. (mainly as dead remains)	77°00'36.3"	015°31'2"–015°31'7"
Ornito-coprophilous tundra	4–5	Ariekammen slope	located 100–150 m high, under strong influence of little auk; samples collected from the soil and moss turf mosaic	highly eutrophic	dry	*Chrysosplenium tetrandrum–Cochlearia groenlandica* communities with *Poa alpina* var. *vivipara*, *Cerastium arcticum*, *Salix polaris*, *Plagiomnium ellipticum*, *Sanionia uncinata*, *Tetraplodon mnioides*, *Dicranum* sp., *Brachythecium turgidum*	77°00'35.9"	015°31'28.3"
High eutrophic wet moss tundra	6–18	Fuglebergsletta marine terrace	located at the base of Ariekammen slope, under the flow of waters from bird colony, moss layer with 70–100% cover; samples collected: sites 6–10 from flows of water on the slope and mosses growing in the tundra; sites 11–14 from mosses and water and from shallow streams; sites 15–18 from puddles with deep water up to 10 cm	highly eutrophic	wet	*Straminergon stramineum*, *Sanionia uncinata*, *Warnstorfia exannulata*, *Aulacomnium palustre*, *Bryum pseudotriquetrum*, *Tetraplodon mnioides*	77°00'32.5"–77°00'33.5"	015°32'30"
Mesotrophic wet moss tundra	19–24	Fuglebekken catchment	located 500–700 m from the base of Ariekammen slope, under moderate influence of *Alle alle*; samples collected: sites 19–21 from streams, deep up to 40 cm, with silty, gravelly or stony bottom; sites 22–24 between mosses	meso-trophic	wet	*Sanionia uncinata, Polytrichum* sp., *Warnstorfia sarmentosa*, *Straminergon stramineum*, *Tetraplodon mnioides, Ptilidium ciliare*, *Cetrariella* sp., *Saxifraga oppositifolia*, *S. rivularis*	77°00'32.0"–77°00'33.5"	015°31'9"–015°32'5"
Flooded moss tundra	25	Fuglebekken catchment	located 700 m from the base of Ariekammen slope, without bird influence; samples collected from the bottom and from rocks in a broad stream, depth up to 30 cm	oligo-trophic	wet	*Sanionia uncinata, Warnstorfia sarmentosa*, *Straminergon stramineum*, *Aulacomnium palustre*, *Bryum pseudotriquetrum*	77°00'33.0"	015°33'50"

Table 1 – *continued*.

Initial stage of cyano-bacteria-moss tundra	26–28	Fuglebekken catchment	located on initial soils, close to lateral moraine Hansbreen, 600–850 m from the base of Ariekammen slope, without bird influence; samples collected from moist soil and small pockets	oligo-trophic	wet	cyanobacteria crusts with *Anthelia juratzkana*, *Sanionia uncinata*, *Saxifraga cespitosa*, *S. oppositifolia*	77°00'33.0"	015°33'50"
Oligotrophic wet moss tundra	29–30		located 700–800 m from the base of Ariekammen slope, without bird influence; samples collected from mosses and slow streams	oligo-trophic	wet	cyanobacteria crust with *Sanionia uncinata, Warnstorfia sarmentosa, Straminergon stramineum, Aulacomnium palustre, Bryum pseudotriquetrum*	77°00'32.0"	015°32'8"
Polygonal tundra	31–34		located on patterned ground, 700–850 m from the base of Ariekammen slope, without bird in-fluence; samples collected from soil	oligo-trophic	modera-tely wet	cyanobacteria crusts with *Racomitrium lanuginosum*, *Anthelia juratzkana*, *Sanionia uncinata*, *Bryum* sp., *Politrychum* sp. and *Saxifraga oppositifolia*, *S. cespitosa*, *Juncus biglumis*, *Equisetum arcticum*, *Sagina nivals*	77°00'30.5"	015°32'90"
Mesotrophic wet moss tundra	35–36	Fuglebergsletta marine terrace	located 700 m from the base of Ariekammen slope, under moderate influence of *Alle alle*; samples collected from soil and mosses grow-ing in the tundra	meso-trophic	wet	*Sanionia uncinata* and *Straminergon. stramineum*, *Tetraplodon mnioides*, *Bryum* sp., *Polytrichum* sp., *Ptilidium ciliare*, *Warnstorfia sarmentosa* and *Cetrariella* sp.	77°00'33.5"	015°32'5"
Oligotrophic flowing water moss tundra	37–38		located 850–900 m from the base of Ariekammen slope, without bird influence; samples collected from slowly flowing, shal-low streams with water from melting snow	oligo-trophic	wet	*Sanionia uncinata*, *Straminergon stramineum*, *Warnstorfia exanulatus*, *Barbula* sp.	77°00'13.5"	015°32'10"
Snowbed cyanobacteria -moss tundra	39–40	Fuglebekken catchment	located 850–900 m from the base of Ariekammen slope, from area with long-lasting snow cover without bird influence; samples collected from soil	oligo-trophic	damp	cyanobacteria crusts with *Sanionia uncinata*, *Saxifraga oppositifolia*, *S. cespitosa*, *Anthelia juratzkana*, *Ochrolechia frigida*, *Cetrariella delisei*	77°00'13.0"	015°32'38.7"
Mesotrophic flooded moss tundra	41–43		located 900–100 m from Ariekammen slope, under influence of little auk; samples collected from the stream and among clumps of moss	meso-trophic	wet	*Sanionia uncinata*, *Polytrichum* sp., *Warnstorfia sarmentosa*, *Straminergon stramineum* and *Saxifraga oppositifolia*, *S. rivularis*	77°00'33.5"	015°32'5"

Table 1 – *continued*.

Cyanobacterial mats tundra with *Saxifraga oppositifolia*	44–47	Fuglebergsletta marin terace	located on low slope with stream water, 900–100 m from Ariekammen slope, without bird influence; samples collected from the cyanobacterial mats among clumps of mosses	oligo-trophic	periodical supply of water	cyanobacteria mats with *Saxifraga oppositifolia*, *Sanionia uncinata*, *S. cespitosa*	77°00'13.0"	015°32'38.7"
Wet cyanobacteria mats tundra	48–49		located 1000–1050 m from the base of the slope, outflow of underground water among coarse rock fragments and stones, without bird influence; samples collected from the surface of soil, surface of coarse rock fragments and stones	oligo-trophic	wet	*Sanionia uncinata*	77°00'11.0"	015°32'43.5"
Oligotrophic flowing water moss tundra under influ-ence of sea spray	50		located near the shore, under influence of sea spray; samples collected from temporally dried up stream with depth of 15 cm	oligo-trophic	wet	cyanobacteria mats with *Paludella squarrosa*, *Sanionia uncinata*	76°59'50"	015°31'60"
Flowing water cyano-bacterial mats tundra	51–52		streams and pools with depth between 10 and 30 cm, the bottom covered in sludge, gravel or rocks, without bird influence; samples col-lected from the bottom of streams spreading broadly on eroded ground and small moss surfaces	oligo-trophic	permanent supply of water	cyanobacteria mats, *Paludella squarrosa*, *Sanionia uncinata*	77°00'12.0"	015°28'65"
Oligo-mesotrophic wet moss tundra	53–54		under little influence of birds; samples col-lected from moss tundra pools and among the mosses	oligo-meso-trophic	wet	cyanobacteria crust with *Sanionia uncinata*, *Straminergon stramineum*, *Polytrichum* sp., *Warnstorfia sarmentosa*, *Saxifraga oppositifolia* and *S. rivularis*	77°00'13.00"	015°29'9.5"
Wet oligo-trophic cyano-bacterial mats tundra	55–58		without bird influence; samples collected from moist soil surfaces with numerous pockets with rain and exudation water	oligo-trophic	permanent supply of water	*Saxifraga oppositifolia* communitiy with *Saxifraga cespitosa*, *Salix polaris*, *Sanionia uncinata*, *Ochrolechia frigida*	77°00'13.0"	015°30'30"

Results and discussion

Diversity of cyanobacteria and green algae in studied ecosystems. — Phycological studies identified 141 taxa of cyanobacteria and green algae, among which 100 species belonged to Cyanobacteria and 41 to Chlorophyta. The characterization of the habitats was based on cyanobacteria species, whereas Chlorophyta species were included either for their dominant role in the habitat or their characteristics distinguishing habitat.

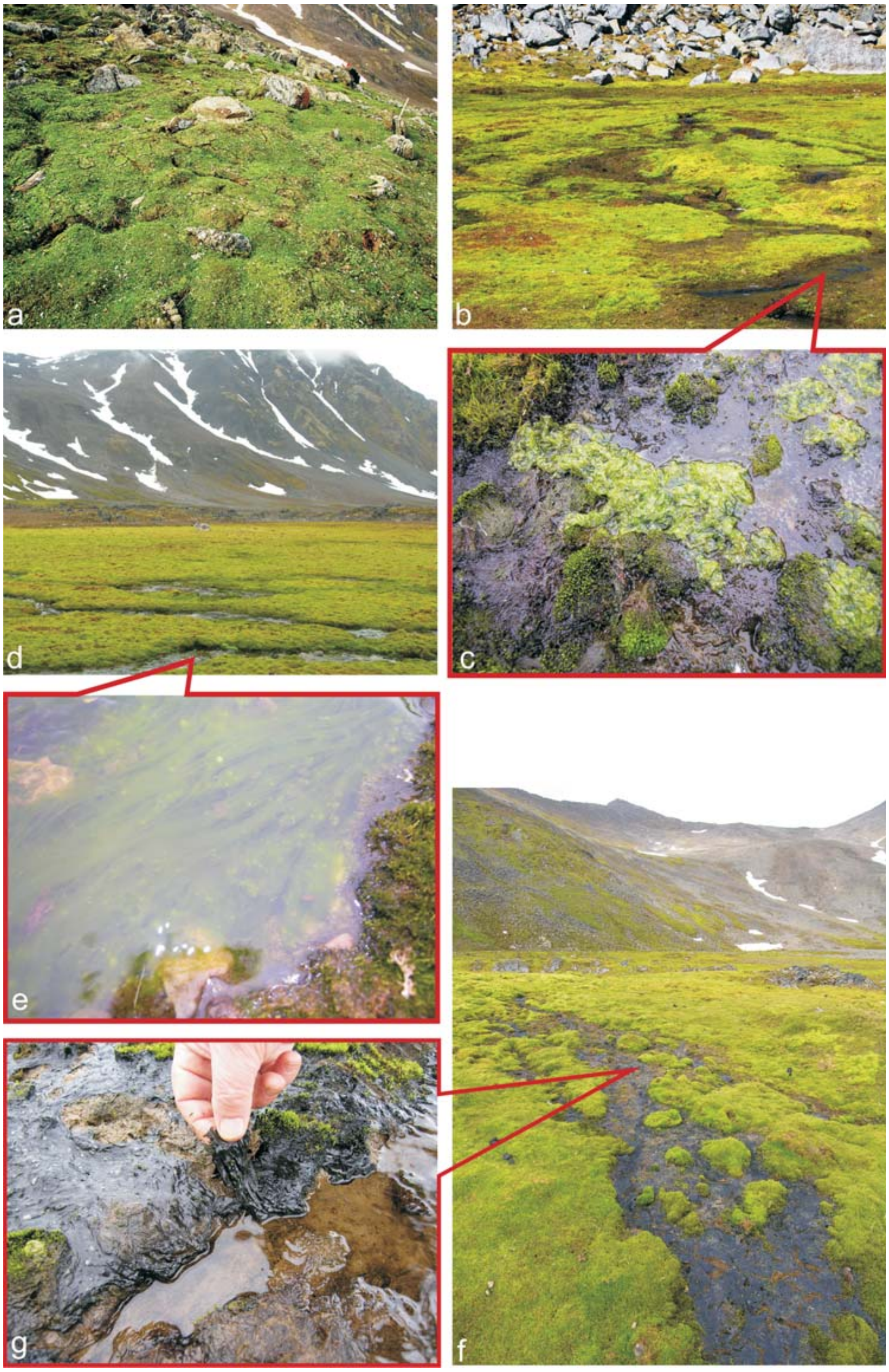
Within the Cyanobacteria group 36 coccoid type of species were discovered, as well as 18 heterocytous filamentous species and 46 non-heterocytous filamentous species. Within the Chlorophyta group the study revealed desmids (20 species), filamentous green algae (9 species) and coccoid and non-filamentous green algae (12 species). In the studied tundra, in various zones and with various bird influence, the species composition of cyanobacteria and green algae assemblages varied significantly (Table 2). Within the habitats there were dominant and distinctive species. Similar habitats were combined to create tundra types as a supplement to the tundra distinguished earlier on the basis of mosses and vascular plants (by Wojtuń and Matuła, unpublished data) (Table 1).

Community analyses. — As a result of the Cosine Theta analysis based on the species composition of cyanobacteria and green algae, a dendrogram was obtained, where the habitats were arranged into separate groups and subgroups according to the types of tundra distinguished on the basis of moss and vascular plant communities' composition with different humidity and trophy (Figs 4, 5).

The first cluster (I) showed a similarity between cyanobacteria and green algae communities occurring on ornithocoprophilous, high eu- and mesotrophic tundra with various degrees of humidity (Fig. 5). In the second, less homogeneous cluster (II), there were cyanobacteria and green algae communities occupying oligotrophic habitats with various humidity (Fig. 5).

Cluster I includes phycoflora habitats with dominating *Prasiola crispa* and *Phormidium autumnale* along with a numerous group of non-heterocytous cyanobacteria, located on ornithocoprophilous, high eutrophic and mesotrophic wet moss tundra (Fig. 4). Within this cluster the phycoflora communities formed 2 groups, 1 and 2, differing in the proportion of dominants and species richness. In group 1 there were three subgroups (1a–c) with various proportions of *P. crispa* (40–100% in the community), which, depending on the humidity, formed various forms of thalli (Table 2, Fig. 4). In group 2 the dominant role was taken by *P. autumnale*, whose proportion was between 40 and 50% in cyanobacteria and green algae communities. The proportion of *P. crispa* in the community, however, decreased to 3–5%, and only young filaments were recorded (Table 2, Fig. 4).

The second cluster (II) (Fig. 4) includes communities of cyanobacteria and green algae inhabiting tundra with various degrees of humidity, formed on oligotrophic habitats. Occurrence of many heterocytous species not found in the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first cluster is characteristic of the second (Table 2). Six groups (3–8) were distinguished in this cluster on the basis of dominants, sub-dominants and characteristic species. Group 3 comprises communities with dominance of the granular form of *Leptolyngbya* sp. and *Oscillatoria* cf. *ornata.* Group 4 includes three subgroups (4a–4c) of soil habitats with the dominance of cyanobacteria crusts with the aerophytic form of *Schizothrix lacustris* and *Nostoc commune*. Habitats included in group 5 were wet habitats covered with cyanobacterial mats, formed in a community of the subaerophytic form of *Schizothrix* cf. *lacustris*. Group 6 comprises of strongly humid habitats with the dominance of the plankton form of *Schizothrix* cf. *lacustris*. In group 7 there is an individual habitat of a broad stream formed by sea sprays, with the dominance of cyanobacteria mats with *Geitlerinema acutissimum* and *Lyngbya aestuarii.* The most distinguishable phycoflora is found in group 8, which comprises of habitats with dominating *N. commune*, *Dichothrix gypsophila* and the brown sheath form of *Tolypothrix* sp. and cyanobacteria mats with *Schizothrix* cf. *calcicola*, not recorded in any of the previous habitats (Table 2; Fig. 4).

Cyanobacteria and green algae in relation to tundra types. — The particular climatic and environmental conditions of the Arctic influence the formation of particular tundra communities with a large proportion of cyanobacteria and green algae. The specific habitat conditions in the area caused by bird colonies and the highest concentration of excrements (Akiyama *et al.* 1986; Smykla *et al.* 2007; Jakubas *et al.* 2008) led to the formation of a community with a clear dominance of *Prasiola crispa*. It is a typical species in polar and cold-temperate regions, where it is usually associated with habitats rich in organic nitrogen (Klekowski and Opaliński 1986; Olech 1990; Graeve *et al.* 2002; Holzinger *et al.* 2006; Matuła *et al.* 2007; Karsten *et al.* 2009; Richter *et al.* 2009; Kosugi *et al.* 2010; Broady *et al.* 2012). In that zone the ornithocoprophilous tundra with *Prasiola crispa* occurs and it is located in the direct vicinity of the nesting birds (sites 1–3). This zone is almost completely void of vascular plants, and it is covered by *P. crispa* (80% to 100%), which covers the ground and dead mosses. It occurs as monostromatic lamellar, cracked form, which is connected with the degree of surface humidity (the habitat is in risk of drying up in summer) (Tables 1, 2, Figs 4, 5).

The further the study locations were from grounds trampled by little auks, the more the ornithocoprophilous tundra (sites 4–6) was covered with rare moss clusters and vascular plants. The proportion of *P. crispa* in the community decreased by about 70%, and there were other species between its lobes, such as brown filaments of *Phormidium autumnale* and elastic, dirty-gray crusts with the short cell

← Fig. 2. Study area: **a**, Ornitocoprophilous tundra with *Prasiola crispa* (subgroup 1a); **b**, High eutrophic wet moss tundra (subgroup 1b) and *P. crispa*'s typically leafy form (**c**); **d**, Mesotrophic wet moss tundra (subgroup 2) with *Ulothrix* ssp. (**e**); **f**, Mesotrophic wet moss tundra (subgroup 2) with *Phormidium autumnale* (**g**).


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form of *Leptolyngbya valderiana* (sub-dominants). The study also revealed that the crusts had a significant proportion of coccoid and non-filamentous green algae (Table 2) and *Merismopedia* sp. – a species considered typical for plankton (Komárek J. and Anagnostidis 1999). In this case cyanobacteria crusts and gelatinous envelopes of coccoid green algae protect it from drying up and create a sufficiently humid habitat. Uncovered soil also had *Klebsormidium* sp. thalli in the form of green coating. The *Klebsormidium* species owes its survival ability to the resistance to drying up (Elster *et al.* 2008).

At the base of the Ariekammen slope within high eutrophic wet moss tundra (sites 7–18) the dominating and distinctive species was still *Prasiola crispa*, which formed a morphologically different thallus (typically the leafy form), which is associated with increased habitat humidity. The proportion of *P. crispa* in the phycoflora community decreased in comparison to ornithocoprophilous tundra by 40–50%. At the same time the study revealed an increase in *Phormidium autumnale* quantity; covering mosses formed dark brown, thin thalli accompanied by *Leptolyngbya valderiana* (sub-dominant) (Table 2). High eutrophic wet moss tundra was characterized by the presence of *Scotiella* spp. and filamentous cyanobacteria without heterocytes, such as the granular form of *Leptolyngbya* sp., *Komvophoron minutum*, *Lyngbya* sp. and *Pseudanabaena catenata*.

In mesotrophic flooded moss tundra (sites 41–43) the dominating species was *Phormidium autumnale*, which had a 50–60% representation in the communities. It occurred in water and at the bottom of the streams in the shape of long, thin, brown thalli breaking up into individual filaments. In polar regions *P. autumnale* is characteristic of streams and humid subaerophytic habitats (Vincent 2000; Komárek J. and Elster 2008; Strunecký *et al.* 2012). In Hornsund tundras it is found in every nitrophilous habitat.

The presence of *Prasiola crispa* decreased by about 20–30% in the community and occurred in the form of young filaments. The species distinctive for this tundra was *Schizothrix* cf. *facilis* (sub-dominant), occurring as long filaments in water and at the bottom of streams, and *Chamaesiphon rostafinskii*, growing on them. These species are thought to be distinctive for fast streams (Komárek J. *et al.* 2012), but in the studied habitat they occurred in a slowly flowing, wide stream. There were also large quantities of *Pseudanabaena frigida*, which has a broad spectrum occurrence in relation to trophy and surface (Fumanti *et al.* 1995; Fumanti *et al.* 1997; Matuła *et al.* 2007; Richter *et al.* 2009; Davydov 2014), but occurs most often in mesotrophic flooded moss tundra. The study also recorded species such as *Tetraspora gelatinosa* and *Geitlerinema acutissimum* (Table 2).

← Fig. 3. Study area: **a**, Snowbed cyanobacteria-moss tundra (subgroup 4b) with details of cyanobacteria crust and *Nostoc commune* (**b**); **c**, Initial stage of cyanobacteria-moss tundra (subgroup 4c) with details of cyanobacteria crust (**d**); **e**, Polygonal tundra (subgroup 4b); **f**, Mesotrophic flooded moss tundra (subgroup 1c); **g**, Flowing water cyanobacterial mats tundra (subgroup 8); **h**, Cyanobacterial mats tundra with *Saxifraga oppositifolia* community (subgrup 5).

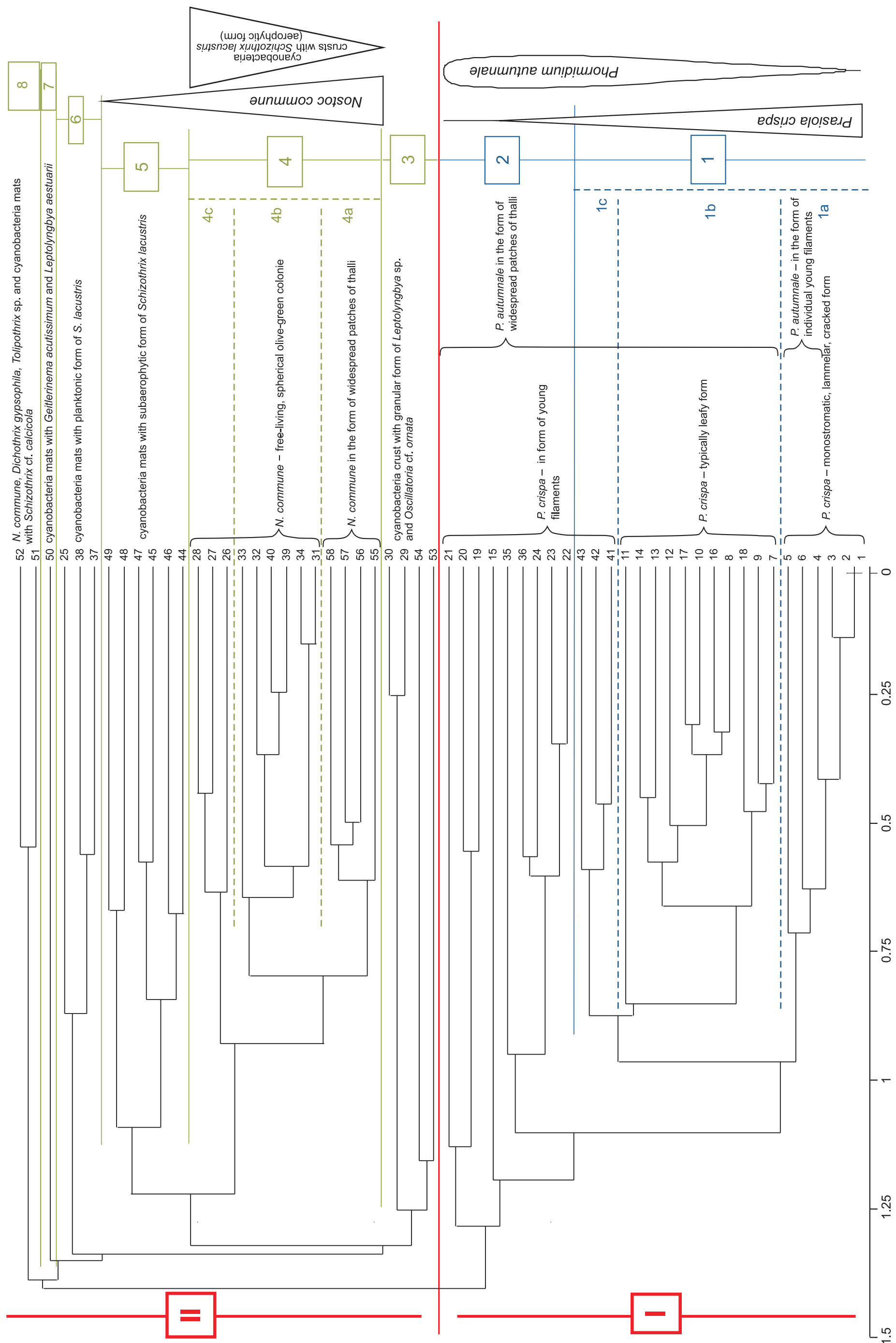

Fig. 4. Hierarchical cluster Cosine Theta analysis based on the similarity of cyanobacteria and green algae communities included in the quantities of the species; 1–58, sampling points; 1–8, type of algae and cyanobacteria communities.

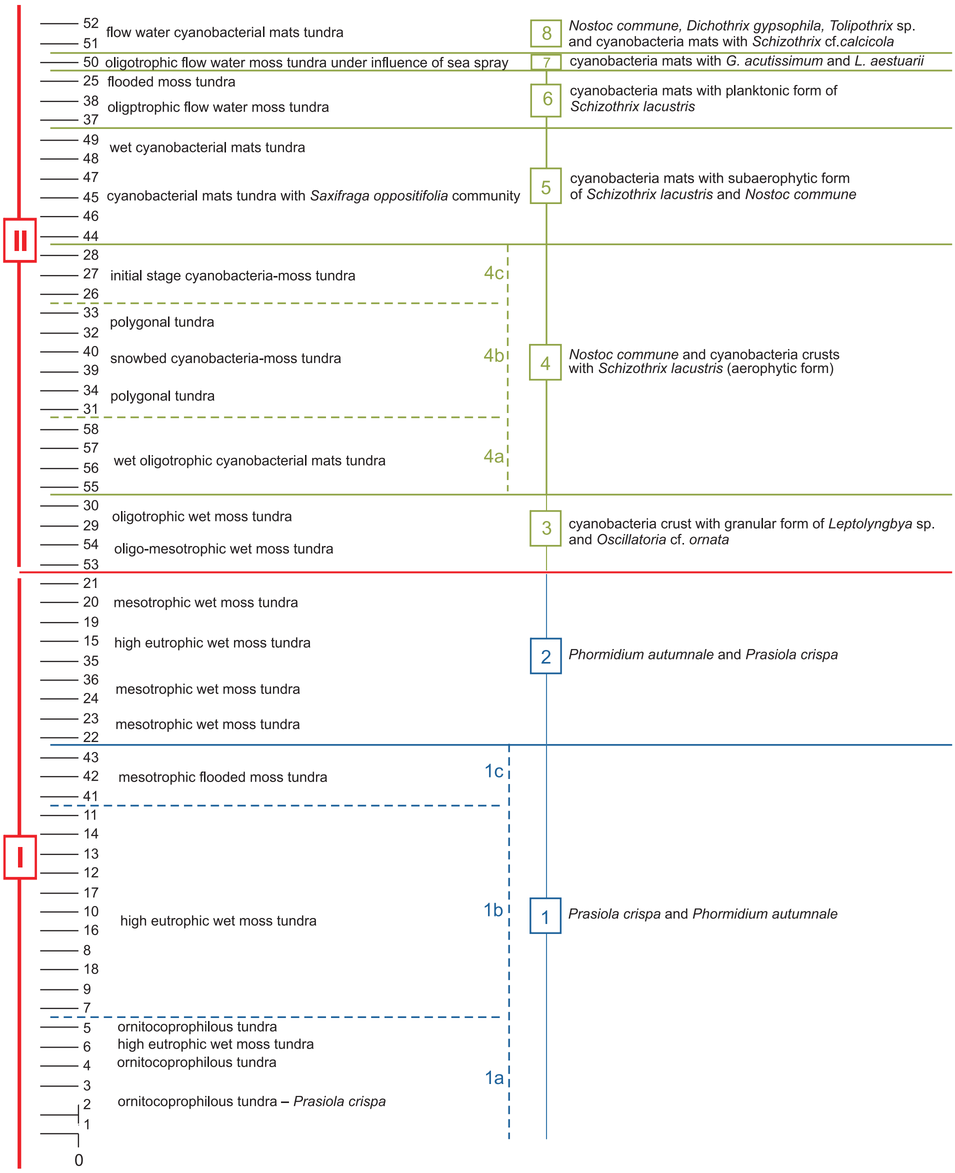

Fig. 5. Hierarchical cluster Cosine Theta analysis based on the similarity of cyanobacteria and green algae communities included in the quantities of the species, showing their connection to the types of tundras distinguished on the basis of mosses and vascular plants; 1–58, sampling points; 1–8, type of algae and cyanobacteria communities.

Mesotrophic wet moss tundra (sites 19–24, 35–36) was also characterized by the dominance of *Phormidium autumnale*, whose proportion in the community was between 40 and 60%. It occurred as brown, thin thalli on mosses, rocks and wet soil. Between the leaves of mosses there were also lobular thalli of the thin

Table 2

Type of tundra, their characteristics according to the cyanobacteria and green algae flora. A–I, the number of species of particular groups of cyanobacteria and algae: A, coccoid type of cyanobacteria; B, non-heterocytous type of cyanobacteria; C, heterocytous type of cyanobacteria; D, total of cyanobacteria; E, desmids; F, coccoid and non-filamentous type of green algae; G, filamentous type of green algae; H, the total of green algae; I, the total of cyanobacteria and green algae.

Type of tundra	groups	sub-groups / sites	Cyanobacteria A	B	C	D	Green algae E	F	G	H	I	Cyanobacteria and green algae (dominant, sub-dominant, characteristic and common species)
Ornitocoprophilous tundra with *Prasiola crispa*	1	1a / 1–3	5	13	0	18	0	3	3	6	24	*Prasiola crispa* community, dominant and distinctive species: monostromatic lamellar, cracked form of *P. crispa* (80–100% soil surface)
Ornitocoprophiolus tundra		1a / 4–6										dominant and distinctive species: *P. crispa*, monostromatic lamellar, cracked form, 70% soil surface; subdominant: *Phormidium autumnale, Leptolyngbya valderiana*; other distinctive species: *Klebsormidium* sp., *Merismopedia* sp. and coccoid green algae
High eutrophic wet moss tundra		1b / 7–18	3	11	0	14	3	5	4	12	26	dominant: *Prasiola crispa* typically leafy form (40–50% soil surface); subdominant: *Phormidium autumnale*, *Leptolyngbya valderiana*; distinctive species: *Scotiella antarctica* f. *svalbardensis*, *Scotiella nivalis*; common species: *Komvophoron minutum*, granular form of *Leptolyngbya* sp., *Pseudanabaena catenata*
Mesotrophic flooded moss tundra		1c / 41–43	4	7	0	11	5	2	3	10	21	dominant: *Phormidium autumnale* 50–60% share in the community; subdominant: *P. crispa* formed as individual young filaments, *Schizothrix facilis*, characteristic species: *Geitlerinema acutissimum*, *Chamaesiphon rostafinskii*, *Tetraspora gelatinosa*; common species: *Pseudanabaena frigida*, *Chroococcus helveticus*
Mesotrophic wet moss tundra	2	– / 19–24, 35–36	4	13	0	17	6	1	6	13	30	dominant: *Phormidium autumnale* 40 to 50% share in the community, subdominant: thin walls form of *Leptolyngbya* sp. and *P. crispa*; distinctive species: *Ulothrix subtilis*, *U. aequalis*, *U.* cf. *oscillarina*; a lot of species of desmids and non heterocystous types of cyanobacteria
Oligo-mesotrophic wet moss tundra	3	–	6	6	3	15	6	0	2	8	23	dominant: cyanobacteria crust with granular form of *Leptolyngbya* sp.; subdominant: *Nostoc commune*, *N.* cf. *punctiforme*; distinctive species: *Oscillatoria* cf. *ornata*; common species: *Scytonema crustaceum*, *Microcoleus vaginatus*, *Gloeocapsa punctata*, *G. tornensis* and desmids
Oligotrophic wet moss tundra		53–54 29–30										
Wet oligotrophic cyanobacterial mats tundra	4	4a / 55–58	18	7	5	30	2	2	0	4	34	dominant: *Nostoc commune* (vast, leathery thallus) and cyanobacteria soil crust (subdomianat) with aerophitic form of *Schizothrix* cf. *lacustris*, *Microcoleus vaginatus*, *Tolypothrix tenuis*, *Gloeocapsa* spp. and *Chroococcus turgidus*

Table 2 – *continued*.

Polygonal tundra	4	4b 31–34	6	5	7	18	0	0	0	0	18	dominant: cyanobacteria crust with aerophytic form of *Schizothrix* cf. *lacustris*, *Gloeocapsa punctata*, *Scytonema crustaceum*, *Microcoleus vaginatus, Tolypothrix tenuis*; subdominant *Nostoc commune* (small, round thalli), *N.* cf. *paludosum*; distinctive species: *Stigonema* cf. *mamillosum, Dichothrix gypsophila* (sacconema stage), *Calothrix* cf. *parietana*
Snowbed cyanobacteria-moss tundra		4b 39–40										
Initial stage of cyanobacteria-moss tundra		4c 26–28	5	6	6	17	5	0	0	5	22	dominant: cyanobacteria crust with aerophytic form of *Schizothrix* cf. *lacustris*, *Tolypothrix tenuis*, *Scytonema crustaceum*, *Gloeocapsa biformis*, *G. tornensis*; subdominant: *Nostoc commune*, *N.* cf. *punctiforme*, *N. paludosum*; common species: *Leptolyngbya foveolarum*, *Pseudanabaena frigida* and desmids
Cyanobacterial mats tundra with *Saxifraga oppositifolia*	5	– 44–47	16	9	10	35	2	0	1	3	38	dominant: cyanobacterial mats with subaerophytic form of *Schizothrix* cf. *lacustris*, *Scytonema crustaceum*, *Tolypothrix tenuis*, *Microcoleus vaginatus*, *Symplocastrum* sp. 1, *Gloeocapsa punctata*, *G. biformis*, *Chroococcus turgidus*; subdominant: *Nostoc commune*
Wet cyanobacteria tundra		48–49										
Flooded moss tundra	6	– 25	10	9	4	23	3	0	0	3	26	dominant: cyanobacterial mats with planktonic form of *Schizothrix* cf. *lacustris*, *Gloeocapsa kuetzingiana*, *G. punctata*, *Symplocastrum* sp., *Scytonema crustaceum*, *Microcoleus vaginatus*; subdominant: *Nostoc commune*; common species: *Aphanothece clathrata*, *A. caldariorum*
Oligotrophic flow water moss tundra		37–38										
Oligotrophic flow water moss tundra under influence of sea spray	7	– 50	3	5	3	11	5	0	0	5	16	dominant cyanobacteria mats with *Geitlerinema acutissimum* and distinctive species: *Lyngbya aestuarii*; a lot of species of desmids (*Cosmarium botrytis*, *C. holmiense*, *C. speciosum*, *C. undulatum*, *C. costatum*)
Flow water cyanobacterial mats tundra	8	– 51–52	8	7	4	19	3	0	0	3	22	dominant: *Nostoc commune* (wideaspread patches of thalli) and cyanobacterial mats with *Schizothrix calcicola*, brown sheath form of *Tolypothrix* sp. (characteristic species), *Dichothrix gypsophila*; common species: *Chroococcus turgidus*, *Aphanothece* sp.

form of *Leptolyngbya* sp. (sub-dominant). The proportion of *P. crispa* in the community decreased by 3–5%, and only the form of young filaments was recorded. Streams flowing through the tundra had a lot of species of filamentous green algae belonging to *Ulothrix* spp., desmids (*Cosmarium holmiense*, *C. undulatum*, *C. costatum var. costatum*, *C. speciosum*), and non-heterocystous types of cyanobacteria (*Geitlerinema acutissimum*, *Pseudanabaena catenata*, long cell form of *Leptolyngbya valderiana*, *Oscillatoria fracta*).

Areas outside the influence of bird colonies had habitats with cyanobacteria crusts and mats. The dominance of cyanobacteria communities in the form of crusts and mats results from their accommodation to environmental stresses, such as drastic fluctuations in temperature and drying and radiation (Oleksowicz and Luścińska 1992; Hu *et al.* 2012; Komárek J. and Kovacik 2013). Their formation is aided by filamentous sheath-forming species (e.g. *Schizothrix*, *Microcoleus*) because the presence of a sheath and mucilage can help protect cells against physical desiccation (Mazor *et al.* 1996; Gupta and Agrawal 2008).

In oligo-mesotrophic and oligotrophic wet moss tundra (sites 53–54, 29–30), the study recorded dirty green and gray cyanobacteria crusts formed of granules of *Leptolyngbya* sp. and *Oscillatoria* cf. *ornata*. The study also revealed the presence of such species as *Scytonema crustaceum*, *Microcoleus vaginatus*, *Gloeocapsa punctata*, and *G. tornensis*. The studied tundra is also characterized by a large proportion of *Nostoc commune* and *N.* cf. *punctiforme* (sub-dominant), which formed macroscopic leathery lobes of olive-green thallus (Table 2). The high quantity of *N. commune* thalli may result from a high quantity of *Bryum pseudotriquetrum* in the habitat. Its stems and leaves are often covered with *N. commune* (Shuji 1986). The study also recorded a large proportion of green algae, particularly desmids: *Cosmarium costatum* var. *costatum*, *C. granatum*, *C. holmiense*, *C. hornavense*, *C. speciosum*, *C. undulatum*. These species are among the Arctic alpine group and often occur in communities of moist mosses (Coesel 1979, 1996; Coesel and Meesters 2007).

Wet oligotrophic cyanobacterial mat tundra (sites 55–58) was characterized by the dominance of *Nostoc commune*, forming a vast, leathery thallus on the surface. The sub-dominant species was cyanobacterial soil crust formed of elastic, dirty-gray filaments of the aerophytic form of *Schizothrix* cf. *lacustris* (dominant), accompanied by filaments of *Microcoleus vaginatus* and *Tolypothrix tenuis* and numerous coccoid cyanobacteria: *Chroococcus turgidus*, *Gloeocapsa punctata*, *G. compacta*, *G. biformis*, *G. alpine*, *G. kuetzingiana*. The large quantity of *Gloeocapsa* species in cyanobacterial mats results from their high adaptation to extreme environmental conditions (Friedmann *et al.* 1988).

The surface of polygonal tundra and snowbed cyanobacteria-moss tundra (sites 31–34, 39–40) was covered by elastic, dirty-gray cyanobacterial crusts built of the aerophytic form of *Schizothrix* cf. *lacustris* and *Gloeocapsa punctata*. Among them the study also recorded brown thalli formed by *Scytonema crusta-*

ceum, *Tolypothrix tenuis*, *Microcoleus vaginatus* and, sporadically, *Dichothrix gypsophila* (sacconema stage), *Stigonema* cf. *mamillosum* and *Calothrix* cf. *parietana*. Among the cyanobacterial crusts there were also large quantities of free-living, spherical olive-green colonies of *Nostoc commune* and *N.* cf. *paludosum* (sub-dominant). A distinctive feature of both tundra was the lack of green algae in the phycoflora structure (Table 2).

The initial stage of cyanobacteria-moss tundra (sites 26–28) was dominated by cyanobacterial crust formed of the aerophytic form of *Schizothrix* cf. *lacustris* with a high proportion of the heterocytous species *Tolypothrix tenuis* and *Scytonema crustaceum*, forming a brown-black filamentous thallus. Within the crust there were also numerous species of coccoid cyanobacteria (*Gloeocapsa biformis*, *G. punctata*, *Chroococcus turgidus*) and desmids (*Cosmarium parvulum*, *C. pokornyanum*, *C. subcostatum*, *Euastrum* sp., *Actinotaenium* sp.). Among the crusts the study also revealed small, round leathery olive-green thalli of *Nostoc* spp. – *N. commune* (sub-dominant), *N.* cf. *paludosum*, *N.* cf. *punctiforme* and mosses: *Anthelia juratzkana*, *Sanionia uncinata*.

The cyanobacterial mat tundra with the *Saxifraga oppositifolia* community and wet cyanobacterial mat tundra (sites 44–49) were characterized by the greatest variety of cyanobacteria, especially with respect to heterocytous and coccoid types (Table 2). Cyanobacterial mats (dominant) were formed of the subaerophytic form of *Schizothrix* cf. *lacustris* with *Scytonema crustaceum*, *Tolypothrix tenuis* and *Microcoleus vaginatus*, and occurred as elastic, resilient, nodular and gray mats. Within them there were also small colonies of *Symplocastrum* sp., *Dichothrix gypsophila* and, in large quantities, coccoid species: *Gloeocapsa punctata*, *G. sanguinea*, *G. biformis.* The distinctive feature of this tundra is the presence of macroscopic, spherical or spread, olive-green colonies of *Nostoc commune* (sub--dominant). Its thalli covered up to 50% of uncovered, moist soil in the analyzed habitats. In polar regions *N. commune* may occur in a water environment in association with mosses, but, above all, it is an obligatory taxon for surface habitats (Howard-Williams *et al.* 1986; Fumanti *et al.* 1995; Hirai *et al.* 2004, Fukunda *et al.* 2008, Komárek J. and Elster 2008; Komárek O. and Komárek J. 2010). On surfaces covered with a thin layer of water it may reach macroscopic sizes, which was the case in the studied habitat (Cavacini 2001).

Oligotrophic flow water and flooded moss tundra (sites 25, 37–38) is covered with cyanobacterial mats (dominant) formed mostly of the planktonic form of *Schizothrix* cf. *lacustris*, *Gloeocapsa kuetzingiana* and *G. punctata*, *Symplocastrum* sp., *Scytonema crustaceum* and *Microcoleus vaginatus*. In the mats the study recorded many coccoid species, such as *G. biformis*, *Aphanothece clathrata*, *A. caldariorum*, *A. microscopica*, the aerotope form of *Woronichinia* sp., the granular form of *Gloeothece* sp. and the dark mucilaginous form of *Aphanocapsa* sp. Among the cyanobacterial mats there was also the long cell form of *Nostoc commune* (sub-dominant) in the form of vast, lobular, olive thalli (Table 2).

The wide stream flowing through the oligotrophic moss tundra under the influence of sea spray (site 50) was the habitat least rich in species of all analyzed tundra types. Distinctive habitat conditions shaped under sea sprays caused the dominance of *Lyngbya aestuarii*. It is a species with a large spectrum of occurrence in salty environments (Silva *et al.* 1996; Galil *et al.* 2011; Kothari *et al.* 2013). It was accompanied by *Geitlerinema acutissimum* (sub-dominant), *Leptolyngbya valderiana*, small cells of *Woronichinia* sp. and small amounts of *Nostoc commune*. There was also a surprising abundance of Desmidiaceae species: *Cosmarium botrytis*, *C. costatum*, *C. holmiense*, *C.* s*peciosum*, *C. undulatum* (Table 2).

Flow water cyanobacterial mat tundra (sites 51–52) was characterized by the dominance of *Nostoc commune* forming widespread lobular thalli covering up to 50% of the tundra surface. It is accompanied by *Schizothrix* cf. *calcicola* as subdominant, forming mats white on the surface and green at the bottom. On the surface of the mats there were numerous nodular brown and orange thalli of *Dichothrix gypsophila sensu lato*. The distinctive species for this tundra was the brown sheath form of *Tolypothrix* sp., not recorded in any of the previous habitats. It formed long, dark olive and black filaments on the *Schizothrix calcicola* mats (Table 2). The flora in the phycoflora in this tundra was distinctively different as a result of calcium in the soil, which is confirmed by the presence of *Schizothrix* cf. *calcicola* and *D. gypsophila*, profusely encrusted with calcium carbonate (Komárek J. and Anagnostidis 2005) and *Paludella squarrosa*, the dominant species in the moss rich community, which favors such surfaces (Dierssen 2001).

Conclusions

The research conducted in the area of Hornsund fjord allowed us to characterize the phycoflora occurring on ecologically different tundra. The Cosine Theta analysis arranged the studied habitats in order based on the similarity of cyanobacteria and green algae composition. The obtained groups of habitats are characterized by a unique set of dominating species and by species distinguishing them from other tundra.

The tundra under the influence of bird colonies were characterized by the dominance of nitrophilous species, *Prasiola crispa* and *Phormidium autumnale*, whose proportion varied depending on the level of trophy and the humidity of the habitats. The study also recorded a greater variety of green algae in those tundra.

In tundra located outside bird influence the dominant role belonged to cyanobacteria forming their own associations, which, in certain areas, covered 100% of the ground surface. They are characterized by high diversity in heterocytous species, which had not been previously recorded in highly trophic tundra. These species had a high proportional abundance in their habitats.

The results of categorization of the habitats by their cyanobacteria and green algae communities are consistent with the types of tundra distinctive for vascular vegetation and mosses, and, at the same time, these results are related to the humidity and trophy of the studied habitats.

The conducted research showed that cyanobacterial and algal communities have a significant role in forming tundra communities in the area and that they need to be taken into account in the characterization of said tundra.

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