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Freshwater mineral nitrogen and essential elements in autotrophs in James Ross Island, West Antarctica

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Abstract: The lakes and watercourses are habitats for various communities of cyanobacteria and algae, which are among the few primary producers in Antarctica. The amount of nutrients in the mineral-poor Antarctic environment is a limiting factor for the growth of freshwater autotrophs in most cases. In this study, the main aim was to assess the availability of mineral nitrogen for microorganisms in cyanobacterial mats in James Ross Island. The nitrate and ammonium ions in water environment were determined as well as the contents of major elements (C, N, P, S, Na, K, Ca, Mg, Al, Fe, Mn) in cyanobacterial mats. The molar ratios of C:N, C:P and N:P in mats were in focus. The growth of freshwater autotrophs seems not to be limited by the level of nitrogen, according to the content of available mineral nitrogen in water and the biogeochemical stoichiometry of C:N:P. The source of nutrients in the Ulu Peninsula is not obvious. The nitrogen fixation could enhance the nitrogen content in mats, which was observed in some samples containing the *Nostoc* sp.

Key words: Antarctica, cyanobacteria, algae, nutrients.

Introduction

Most of the biomass of the Antarctic non-marine ecosystem is accumulated in lakes and ponds. Microbial mats are communities of vertically stratified organisms occurring in streams, ponds, lakes, and seepages, mostly composed of cyanobacteria. The morphology, structure, and colour are determined by the composition of heterotrophic and photoautotrophic organisms, the incorporated inorganic material, and environmental conditions. The expansion of algae in Antarctic glacial streams and lakes depends considerably on the content of available nitrogen, especially nitrate-nitrogen (Elster *et al.* 2002; Nedbalová *et al.* 2013). Nitrogen uptake is an endogenous process stimulated by light (Hawes and Brazier 1991). The growth of organisms stops with nitrogen depletion. The next growth is supported by the slow decomposition of organic matter (perished cells of cyanobacterial mats and mosses) and nitrogen fixation from the atmosphere by cyanobacteria (Elster *et al.* 2002). The level of nitrogen fixation upon nutrient uptake by microbial mats varies in different parts of Antarctica (Fernández-Valiente *et al.* 2007). Generally, microbial mats in the Antarctic ecosystem are nitrogen limited (Gooseff *et al.* 2004). However, a recirculation of nutrients within the mat matrix may occur, which is indicated by increased nutrient concentrations in pore water within the mats (Fernández-Valiente *et al.* 2007). Processes of the biogeochemical cycling of nitrogen forms (Hanrahan and Chan 2005) cause changes in chemical forms, which also affect actual ion concentrations in water environment. The NO_3^- ion is predominant under oxidizing conditions, the NH_4^+ ion under reducing conditions (Hanrahan and Chan 2005).

Nutrient stoichiometry can determine the species composition and the rate of growth (Hecky *et al.* 1993). However, the ratio of C:N:P is partially season dependent. The highest nutrient intake in Arctic lakes is observed during spring melting, after which the nutrients are subjected to internal nutrient recycling for the rest of the growth season. A sufficient amount of nutrients in the early season followed by minimal nutrient availability can cause high C:N and C:P ratios for the remainder of the season (Dobberfuhl and Elser 2000). The ratios of C:N and C:P in primary producers are also influenced by the balance between light and available nutrients (Cross *et al.* 2005). A high intensity of photosynthetically active radiation (PAR) can also increase the C:P ratio; conversely, ultraviolet radiation may reduce the C:P and N:P ratios. This stoichiometric response can affect the biogeochemical cycle of phosphorus. The high intensity of PAR at low levels of inorganic phosphorus influences carbon fixation in autotrophs and increases the C:P ratio. Ultraviolet radiation causes physiological changes in intracellular morphology, which also affects the nutrient intake (Hessen *et al.* 2008). The variability in phosphorus content can also be explained by the competition between bacteria and primary producers or the potential ability of microorganisms to substitute elements (Danger *et al*. 2007). The greatest competition was observed at low concentrations of nutrients (Cotner *et al*. 2010). The ratio of N:P can characterize the relative quantity of cyanobacteria with nitrogen fixation ability (Vanni *et al*. 2011). If the C:N ratio is relatively static and the N:P ratio is highly variable, then the bacteria play a fundamental role in the balance of phosphorus in lake ecosystems (Cotner *et al*. 2010). Generally, the concentration of nutrients in water is dependent on the actual consumption by organisms. Thus, it depends on the time of the day, solar activity, and temperature (Coufalík *et al*. 2013). Therefore, the minimum concentration of mineral nitrogen can be observed in the late afternoon (Hawes and Brazier 1991). Nevertheless, unbalanced C:N:P ratios in autotrophs biomass together with the levels of nutrients in the water column can reasonably be used as a first proxy of nutrient limitation of primary producers in the Antarctic water ecosystems.

The aim of this study was to distinguish whether the freshwater habitats on James Ross Island are nitrogen limited or not. The determination of the content of available mineral nitrogen in freshwater environments on James Ross Island in the summer season and possible evaluation of nitrogen sufficiency in selected habitats according to the content of essential elements in cyanobacterial mats were in focus.

Study area

According to a recent biodiversity classification of Antarctica, James Ross Island belongs to the North-East Antarctic Peninsula (Terauds *et al*. 2012). The Ulu Peninsula located in the northern part of James Ross Island represents one of the largest ice-free Antarctic territories. The location in the precipitation shadow of the Antarctic Peninsula, which forms a barrier to prevailing westerly winds, gives the Ulu Peninsula a semi-arid outlook (Davies *et al*. 2013), when compared with other areas of Maritime Antarctica. Only small land-terminating glaciers of different types remain here (Carrivick *et al*. 2012). On the other hand, this deglaciated ice-free area represents a location with numerous types of freshwater lakes, which evolved after glacier retreats and some of which have been stable on the scale of millennia (Nedbalová *et al*. 2013). Many of the lakes are still fed by melt water from retreating glaciers (Davies *et al*. 2013); however, other lakes are fed from snowfields only and may dry out during years with insufficient snow accumulation (Váczi *et al*. 2011). The origin, bedrock geology, geomorphology, hydrological stability and physical and chemical characteristics of the lakes are described in Nedbalová *et al*. (2013). A description of the sampling sites for autotrophic organisms is published in detail in Skácelová *et al*. (2013). The geochemical rock signatures are characterized in Košler *et al*. (2009).

Methods

The sampling of water and freshwater autotrophs was carried out during the Czech Antarctic expedition to James Ross Island in the 2012/2013 season. Coordinates and dates of sampling are presented in Table 1; the localities are also marked in Fig. 1. The following localities were selected for this study: Johnson Mesa Lake, Monolith Lake, the Lachman Lakes and Interlagos ponds, unnamed temporary pools, seepage near the *J.G. Mendel* Station, and the Bohemian Stream (Fig. 1). Johnson Mesa Lake in young moraine landscape (Bibby Lake in Nedbalová *et al*. 2013) was visited three times for the sampling of lake water. The sampling of mat was performed during maximum thawing of the lake, but, even so, a part of the surface was still under the ice. Monolith Lake, a stable lake in old moraine landscape, represents another type of habitat. In addition to samples of water from the lake inflow near the sampling sites for microbiota (Monolith Lake inlet), water samples from the lake and its outlet were also collected. The Lachman Lakes with the Interlagos ponds were the third type: shallow coastal lakes with an inflow of meltwater from snowfields.

Besides stable bodies of water, temporary pools with developed communities of microbial mats were also studied. The selected pools near the coast occur only in particular seasons. The seepage near the *J.G. Mendel* Station is supplied primarily with water from the snowfield. Samples of water and microorganisms were collected from shallow pools of the seepage. Water samples from the Bohemian Stream were collected along the entire length of the watercourse, from the snowfield to the sea, nine samples in total.

Water samples were collected in PE (polyethylene) vials (50 ml) and transported immediately to the *J.G. Mendel* Station laboratory. Samples of cyanobacterial mats were also collected using PE vials and stored at 4°C. Samples were transported to the Czech Republic in a cooling box at a temperature slightly above 0°C. Individual species of autotrophs in the collected samples were identified according to morphological characteristics. The temperature, pH, and conductivity of water were measured *in situ* using a combined tester (Hanna Instruments). The concentrations of NH_4^+ and NO_3^- in water samples were determined in the station laboratory immediately after the tempering. The potentiometric determination of ions was carried out using a WTW 3310 multimeter (Germany) and combined ion-selective electrodes (THETA 90, Czech Republic). The buffer solutions of K_2SO_4 and LiCl were used for the determination of nitrate and ammonium ions, respectively. Samples of collected microorganisms (in mats) were studied in the Czech Republic by means of optical microscopy (Olympus BX50, Japan). Then, the majority of samples were lyophilised in a Maxi Dry Lyo lyophiliser (Heto-Holten, Denmark) for 72 hours. Lyophilised samples were stored in PE vials at a temperature of 4°C. The homogenisation of samples in agate mortar was performed before

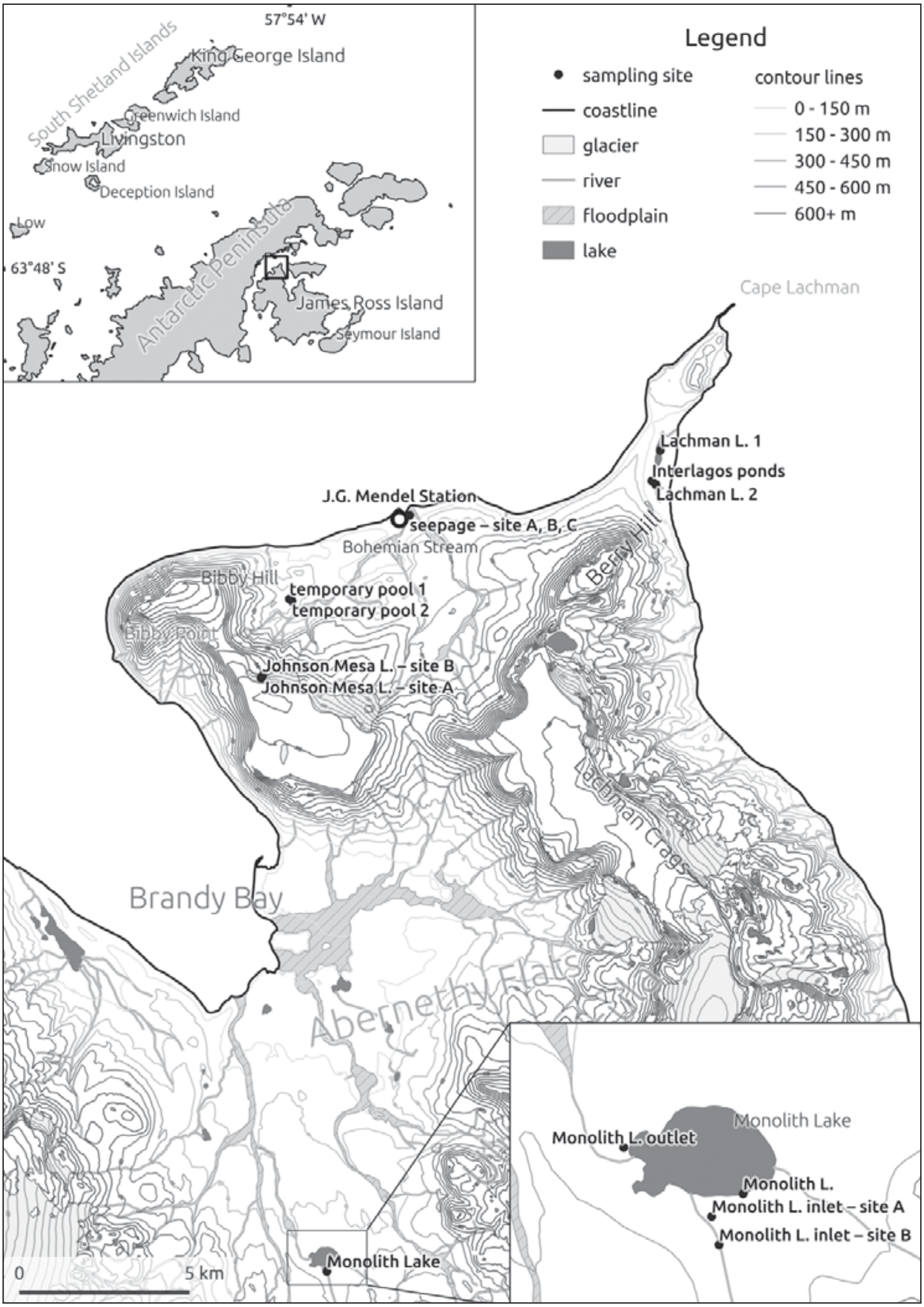

Fig. 1. Selected localities, the northern part of James Ross Island (after CGS 2009).

Table 1

Localities and sampling.

Sample name	GPS	Type of sample	Sampling
Johnson Mesa L. – site A	S63°49’11”, W57°55’54”	biota	29.1.
Johnson Mesa L. – site B	S63°49’10”, W57°55’52”	biota, water	17.1., 29.1., 8.2.
Monolith L. inlet – site A	S63°53’56”, W57°57’21”	biota	3.2.
Monolith L. inlet – site B	S63°53’59”, W57°57’21”	biota, water	3.2.
Monolith L.	S63°53’54”, W57°57’13”	water	3.2.
Monolith L. outlet	S63°53’48”, W57°57’36”	water	3.2.
Lachman L. 1	S63°47’42”, W57°48’22”	water	6.2.
Lachman L. 2	S63°47’58”, W57°48’35”	water	6.2.
Interlagos ponds	S63°47’56”, W57°48’38”	biota, water	6.2.
temporary pool 1	S63°48’35”, W57°55’06”	water	26.1.
temporary pool 2	S63°48’36”, W57°55’04”	water	26.1.
seepage – site A	S63°48’01”, W57°52’46”	biota, water	14.2.
seepage – site B	S63°48’01”, W57°52’45”	biota	14.2.
seepage – site C	S63°48’00”, W57°52’45”	biota	14.2.
Bohemian Stream		water	22.1.

each analysis. Total carbon content in samples was determined by means of a Vario TOC cube analyser (Elementar, Germany). Total nitrogen content was determined using a Kjeltec 2300 analyser (FOSS, Sweden). To determine the levels of P, S, Na, K, Ca, Mg, Al, Fe, and Mn, the samples were digested in a microwave mineraliser (Berghof, Germany) by means of H_2O_2 and sub-boiling HNO_3. The determination was performed using an ICP-OES, iCAP 6500 Duo spectrometer (Thermo, UK).

Results

Species of freshwater autotrophs. — Communities of green algae and cyanobacteria in the studied habitats evinced high species diversity. At least 18 autotrophic organisms were distinguished in the mat sample from Interlagos ponds. A complete list of the determined species, including their relative quantities in the studied samples, was reported by Skácelová *et al*. (2013). The *Cosmarium* sp., *Actinotaenium curtum*, *Staurastrum punctulatum*, and *Chlorobotrys regularis* were reported for James Ross Island for the first time. The dominant species are listed in Table 2.

Table 2

Freshwater algae and cyanobacteria species[a] in mats samples.

Sample name	Frequent taxa	Infrequent taxa
Johnson Mesa L. – site A	*Oscillatoria* sp., Chlorococcales	
Johnson Mesa L. – site B	*Klebsormidium* sp.	*Luticola* sp., *Lyngbya* sp., Chlorococcales
Monolith L. inlet – site A	*Gomphonema* sp., *Zygnema* sp.	*Leptolyngbya vincentii*, *Oscillatoria* cf. *subproboscidea*, Chlorococcales
Monolith L. inlet – site B	*Leptolyngbya vincentii*, *Microcoleus* sp., *Nostoc* sp.[b]	*Calothrix* sp.[b]
Interlagos ponds	*Leptolyngbya erebi*, *Nitzschia* sp., *Nostoc* sp.[b]	*Amphora* sp., *Lyngbya* sp., *Microcoleus* sp., *Phormidesmis* sp., Chlorococcales
seepage – site A	*Leptolyngbya erebi*	*Hantzschia* sp., *Nostoc* sp.[b], *Oscillatoria* cf. *subproboscidea*, *Wilmottia murrayi*, Chlorococcales
seepage – site B	*Leptolyngbya fritschiana*, *Zygnema* sp.	*Actinotaenium curtum*, *Oscillatoria* sp., *Ulothrix* sp.
seepage – site C	*Nostoc* sp.[b]	*Leptolyngbya erebi*, *Oscillatoria* cf. *subproboscidea*

[a] The 41 algal and cyanobacterial taxa are listed in Skácelová *et al*. (2013).
[b] The species with an ability of nitrogen fixation.

Nitrate and ammonium ions in surface water. — Concentrations of nitrate and ammonium ions in water were determined at all studied localities (Table 3). The limits of detection of nitrate and ammonium ions were 0.32 mg L^{-1} and 0.36 mg L^{-1}, respectively. The contents of nitrate and ammonium ions in the Johnson Mesa Lake are presented together with the physico-chemical parameters of the water in Table 3. The lake evinced maximum ice decay on 29th January. It can be seen that the amount of available nitrogen decreased to a minimum at this time. The contents of observed ions in inflow to the Monolith Lake, in lake water, and in outflow from the lake at the beginning of the Monolith Stream evinced the decline in concentrations under the limit of detection. Water conductivity increased slightly after the passage of water through the lake; nevertheless, the values were the lowest recorded. Concentrations of nitrate and

Table 3

Nitrate and ammonium ions in water samples and physico-chemical parameters.

Sample	NO_3^- (mg L^{-1})	NH_4^+ (mg L^{-1})	Temperature (°C)	pH	Conductivity (µS cm^{-1})
Johnson Mesa L. (17.1.)	1.80±0.04	4.10±0.12	9.2	7.7	81
Johnson Mesa L. (29.1.)	0.56±0.01	1.12±0.02	4.0	9.8	80
Johnson Mesa L. (8.2.)	0.62±0.02	3.56±0.11	1.2	9.1	82
Monolith L. inlet	1.36±0.03	0.58±0.02	2.2	8.3	55
Monolith L.	–	–	1.7	8.3	67
Monolith L. outlet	–	–	1.2	8.1	69
Lachman L. 1	1.61±0.02	1.64±0.02	10.8	8.9	240
Lachman L. 2	0.99±0.01	1.19±0.01	10.0	8.2	102
Interlagos ponds	2.23±0.03	1.51±0.02	7.5	9.4	127
temporary pool 1	2.73±0.08	12.8±0.49	4.4	9.5	466
temporary pool 2	1.74±0.04	19.7±0.68	4.4	8.9	674
seepage	0.99±0.02	2.11±0.05	3.5	8.2	174
Bohemian Stream	1.05±0.02–1.55±0.04	0.52±0.01–1.64±0.05	0.5–5.5	8.2–8.6	150–250

– under the limit of detection

ammonium ions in the Lachman Lakes were higher than in the inland Monolith Lake. Relatively high contents of both ions were determined in the Interlagos ponds with the abundant occurrence of microbial communities. An extreme concentration of ammonium nitrogen was observed in un-named temporary pools near the coast west of the *J.G. Mendel* Station. Drying pool floors were covered with cyanobacterial mats. The pools had the highest conductivities of all the localities. In addition to habitats with stagnant or slow-flowing water, in the seepage area near the *J.G. Mendel* Station, concentrations of the studied ions were also determined in water samples from the Bohemian Stream. This watercourse is supplied from several snowfields located in many inflow sub-catchments. The content of both ions showed no clear trend in consumption or enrichment throughout the flow.

Essential elements in cyanobacterial mats. — The nutrient sufficiency in the lakes on James Ross Island was estimated according to the elementary analysis of samples of cyanobacterial mats. Contents of total carbon, nitrogen, phosphorus, and sulphur related to the dry weight of samples are presented in

Table 4. The relative standard deviations (RSD) of these measurements were below 4%, 2%, 1.5%, and 3% for C, N, P, and S, respectively. Molar ratios of C:N, C:P, and N:P were calculated from the contents of C, N, and P in mat samples (not only in autotrophs). The extent of the deficiency in nitrogen and phosphorus in the studied localities was assessed on the basis of the range published by Hecky *et al*. (1993). According to this range, the severe nitrogen deficiency is indicated by the ratio of C:N > 14.6, severe phosphorus deficiency is indicated by ratios of C:P > 258 and N:P > 22. On the basis of the chemical composition of autotrophs, it seems that the content of bioavailable nitrogen in surface water in the studied localities either evinced only a moderate deficit or achieved sufficiency, which corresponds to the determined concentrations of nitrate and ammonium ions in water samples. Nevertheless, the evaluation of nutrient sufficiency of the habitats according to these calculations is not unambiguous. Slight nitrogen deficiency was observed in the inflows to Monolith Lake. The samples differed considerably in their levels of phosphorus deficiency. The highest phosphorus deficit was evinced by the Interlagos ponds; however, nitrogen deficiency was only moderate here. According to the analysis of samples of the seepage biota, the content of available nitrogen in this habitat is sufficient for the nutrition and growth of microorganisms. The seepage contained enough phosphorus according to the samples from sites A and B. However, the sample consisting mainly of *Nostoc* sp. (site C) indicated a serious lack of phosphorus in relation to these criteria.

The evaluation of phosphorus availability was not clear-cut despite the relatively balanced content of phosphorus in biota. The content of phosphorus in water samples was not determined. Therefore, there could be a possible misrepresentation of the evaluation of nutrient sufficiency due to the presence of rock particles and the influence of sea salt aerosol. Thus, the contents of Na,

Table 4

Contents of C, N, P, and S (mg g^{-1}) in mat and molar ratios of C:N, C:P, and N:P.

Sample name	C	N	P	S	C:N	C:P	N:P
Johnson Mesa L. – site A	84	7.5	1.43	1.13	13.1	151	12
Johnson Mesa L. – site B	143	19.5	3.22	1.74	8.6	115	13
Monolith L. inlet – site A	160	17.9	1.17	0.76	10.4	353	34
Monolith L. inlet – site B	95	11.4	1.41	1.35	9.7	174	18
Interlagos ponds	238	26.3	1.40	1.42	10.6	438	42
seepage – site A	109	15.8	2.58	2.53	8.0	109	14
seepage – site B	102	12.5	2.92	2.16	9.5	90	9
seepage – site C	233	38.5	2.28	2.49	7.1	264	37

K, Ca, Mg, Al, Fe, and Mn were also determined (Table 5). Relative standard deviations of the measurements were below 10%, 5%, 3%, 4%, 5%, 3%, and 3% for Na, K, Ca, Mg, Al, Fe, and Mn, respectively. However, the direct effect of sea spray on the concentrations of elements (Na, K, Ca, Mg) in mats was not observed in the studied localities. The lowest content of sodium was found in the sample from the Interlagos ponds, which are located near the coast. The presence of apatite particles in mat would naturally lead to misrepresentation of the phosphorus content in samples and incorrect assessment of the phosphorus sufficiency. Nevertheless, the calcium content was balanced for most samples and evinced a weak negative correlation with the phosphorus content (Pearson correlation coefficient $r = -0.543$, $p = 0.16$). The number of rock particles in samples was estimated by the determination of lithophile elements such as Al and Fe, which correlated with each other ($r = 0.932$, $p = 0.0006$). Accordingly, the sample from Johnson Mesa Lake (site A) with maximum contents of Al and Fe contained the highest proportion of rock. Two samples from seepage contained the lowest Al contents (sites B and C), which could be considered the least affected by inorganic material. These samples evinced considerable agreement in the contents of Ca, Mg, Al, Fe, and Mn, despite the fact that they differed significantly in their molar ratios of C:P and N:P.

Table 5

Contents of macro-elements in mat (mg g^{-1}).

Sample name	Na	K	Ca	Mg	Al	Fe	Mn
Johnson Mesa L. – site A	3.8	6.3	15.2	21.2	37	39	1.19
Johnson Mesa L. – site B	3.9	6.8	10.1	15.3	21	26.9	2.03
Monolith L. inlet – site A	1.8	4.2	12.0	14.3	18.8	28.0	0.35
Monolith L. inlet – site B	2.5	5.1	22.6	15.4	26	35	0.74
Interlagos ponds	1.3	4.1	12.7	10.4	16.9	20.9	0.75
seepage – site A	3.5	6.0	10.2	13.1	26	26.4	0.57
seepage – site B	2.6	12.2	11.9	6.0	9.7	11.2	0.21
seepage – site C	5.4	4.5	12.8	8.9	10.1	10.1	0.21

Discussion

Based on our measurements, it appears that the amount of mineral nitrogen in James Ross Island freshwaters in the summer season is sufficient for the growth of microbial communities in these aquatic environments. In comparison, the concentration of nitrate nitrogen in the ultra-oligotrophic Crooked Lake in the Vestfold Hills (continental Antarctica) is usually up to 10 μg/L and does not exceed 50 μg L^{-1} in winter. The concentration of ammonium nitrogen is mostly up to 25 μg L^{-1} (Butler 1999). The content of inorganic nitrogen in lake water was higher on James Ross Island than on Livingston Island in Maritime Antarctica (Toro *et al*. 2007). The determined concentrations in the Bohemian Stream were also relatively high in comparison to the concentrations in the Potter Peninsula (King George Island) or streams in maritime Antarctica unaffected by animals (Pizarro and Vinocur 2000).

Relatively high concentrations of nitrate and ammonium ions, compared to oligotrophic areas, are without any obvious source in James Ross Island. The eutrophication by macrofauna does not occur in the Ulu Peninsula and many lakes are located in young moraines (Nedbalová *et al*. 2013), which excludes the possibility of contamination from fossil macrofauna sites. The uplifted marine terrace incorporating the Lachman Lakes is inhabited by sea birds causing surface eutrophication, as is obvious from the occurrence of *Xanthoria elegans* lichen in its vicinity (Láska *et al*. 2011). However, the occurrence of sea birds is occasional. The possibility of the release of mineral nitrogen from bedrock has not yet been confirmed (Nedbalová *et al*. 2013). The elevated concentrations of ammonium ions may be caused by the melting of permanent ice or snow (Coulkett and Ellis-Evans 1997), nevertheless, the atmospheric input of nitrates cannot be the only source (Nedbalová *et al*. 2013).

The explanation can consist in biological transformations of nitrogen species in water environment. The release of ammonia could be connected with the decomposition of organic matter (Hanrahan and Chan 2005) and its unbalanced consumption, which can be the reason for the extreme concentrations of ammonium ions in some samples. The concentration of nitrates in water in some areas of Antarctica can be very high, which is explained by freezing and evaporation (Vincent and Howard-Williams 1994). The concentrations of ammonium ions and the conductivity in temporary pools indicated these effects.

However, water surfaces near the coast tend to have enhanced conductivities compared to lakes in a further distance from the sea or in the vicinity of glaciers (Camacho *et al*. 2012), due to the presence of sea spray and animals (Toro *et al*. 2007). The determined pH values and conductivities of the water in the studied localities corresponded to previously published data from the Ulu Peninsula (Hawes and Brazier 1991; Nedbalová *et al*. 2013). Generally, maximum concentrations of ammonium and nitrate nitrogen in lakes were observed under the ice; concentrations fall mainly in the upper layer of water during the summer season (Butler 1999). Moreover, the summer melting of a lake's ice cover increases the circulation of nutrients in the lake (Camacho *et al*. 2012). The observed fluctuation in ion concentrations in the Johnson Mesa Lake could be associated with the ice cover thawing as was marked previously (Nedbalová *et al*. 2013). A steep decline in total dissolved nitrogen together with constant conductivity can also indicate biological processes (Hawes and Brazier 1991).

Nutrients concentrations in surface water are dependent on the geomorphological setting as well. Surprisingly, nitrate concentrations in the Monolith Lake inlet were comparable with concentrations in coastal lakes, ammonium concentrations were lower. Elevated nitrate concentrations further from the coast are not rare (Vincent and Howard-Williams 1994).

The next factor influencing the concentration of ammonium ions is nitrogen fixation, which was observed for *Nostoc* sp., *Nodularia* sp. and *Calothrix* sp. (Hawes and Brazier 1991; Vincent and Howard-Williams 1994). *Nostoc* sp. was abundant in cyanobacterial mats of Interlagos ponds. Nitrogen fixation in cyanobacterial mat increases with temperature (Velázquez *et al*. 2011). During the summer season at this site, the temperature even exceeded 10°C (Váczi *et al*. 2011). However, the concentration of observed ions in water was not higher in this sample than in the others. Thus, the nitrogen fixation could be noticeable from the elemental analysis of the mat samples. The contents of organic carbon and total nitrogen in samples of cyanobacterial mat (Bargagli *et al*. 2007; Velázquez *et al*. 2011) or green algae (Nie *et al*. 2012) do not differ from other areas of Antarctica. Total nitrogen content was highest in the sample from seepage (site C) and in the sample from the Interlagos ponds, which both contained *Nostoc* sp. Geologically young ecosystems tend to be rich in phosphorus (Barrett *et al*. 2007). It seems that the calculation of phosphorus deficiency could probably be influenced by the physiological activity of *Nostoc* sp.

Biogeochemical stoichiometry, which is affected by biological processes, environmental conditions, landscape formation, and geochemistry, is used for evaluating nutrient sources, even in polar regions of the Earth (Barrett *et al*. 2007). Besides, the use of nutrient diffusing substrates or enzymatic bioassays can also be useful for the determination of biofilms nutrient limitations. Mats consist of cyanobacteria, algae, other heterotrophic and autotrophic microorganisms, clastic sediments, and other organic and inorganic material (Velázquez *et al*. 2011). Therefore, assessment depends considerably on the variability of samples – *i.e*. also on the content of inorganic components. The influence of the bedrock can be observed for the Monolith Lake and the Johnson Mesa Lake. The results are certainly affected by the high proportion of aluminium (~8.6%) and iron (6.9–7.9%) in the James Ross Island Volcanic Group (JRIVG) rocks (Košler *et al*. 2009), which form the whole catchment of the Johnson Mesa Lake. A similar situation exists with respect to the Monolith Lake inlets, where aluminium and iron might originate from plentiful blocs of JRIVG hyaloclastite breccia scattered in this area. The high content of calcium in one of the Monolith Lake inlets corresponds to the highly calcareous Cretaceous bedrock in this area. The trend of K- and Mg-enrichment in the Johnson Mesa Lake might correspond to the high potassium (up to 1.8%) and magnesium (4.2–5.3%) contents in JRIVG rock (Košler *et al*. 2009). These contents are comparable with values determined in other parts of Antarctica (Bargagli *et al*. 2007). However, the direct influence of solid particles on the contents of phosphorus in samples was not found. The influence of the sea spray on lake water chemistry was proven primarily for lakes at low altitudes and close to the shore-line (Nedbalová *et al*. 2013), nevertheless, the elemental composition of the mat seems not to be affected.

Conclusions

Communities of cyanobacteria and algae play a key role in the colonization of deglaciated regions of Antarctica. According to the analysis of samples of cyanobacterial mats and the determination of nitrate and ammonium ions in water, it appears that the mineral nitrogen in deglaciated area of the James Ross Island is not a limiting factor for cyanobacteria or algae growth. Thus, the development of communities of microorganisms in lakes in this part of Antarctica could be more dependent on the length of the thermally favourable period than on the content of available mineral nitrogen.

The principle of evaluating nutrient sufficiency according to C:N:P stoichiometry in entire mats may not be generally applicable. The nitrogen sufficiency determined by C:N:P stoichiometry was estimated in agreement with determined concentrations of nitrate and ammonium ions. However, the calculated lack of phosphorus in some habitats appeared to be influenced.

The influence of rock particles in samples was not confirmed as well as the impact of sea spray. The level of available nutrients in aquatic environments is the result of dynamic processes. Variable concentrations of nitrate and ammonium ions in surface water seem to be dependent on the ice cover thawing, the lakes drying up, and physiological activity of cyanobacterial communities.

The nitrogen fixation was observed for *Nostoc* sp. which led to enhanced content of the nitrogen in mat samples containing this species. The subsequent research of the *Nostoc* sp. should be performed in relation to mineral nitrogen content in water environment.

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