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Carbon and nitrogen isotope composition of vegetation on King George Island, maritime Antarctic

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Abstract We report abundance of ^{13}C and ^{15}N contents in terrestrial plants (mosses, lichens, liverworts, algae and grasses) from the area of Barton Peninsula (King George Island, maritime Antarctic). The investigated plants show a wide range of $\delta^{13}C$ and $\delta^{15}N$ values between −29.0 and −20.0‰ and between −15.3 and 22.8‰, respectively. The King George Island terrestrial plants show species specificity of both carbon and nitrogen isotope compositions, probably due to differences in plant physiology and biochemistry, related to their sources and in part to water availability. Carbon isotope compositions of Antarctic terrestrial plants are typical of the C_3 photosynthetic pathway. Lichens are characterized by the widest carbon isotope range, from −29.0 to −20.0‰. However, the average $\delta^{13}C$ value of lichens is the highest (−23.6 ± 2.8‰) among King George Island plants, followed by grasses (−25.6 ± 1.7‰), mosses (−25.9 ± 1.6‰), liverworts (−26.3 ± 0.5‰) and algae (−26.3 ± 1.2‰), partly related to habitats controlled by water availability. The $\delta^{15}N$ values of moss samples range widest (−9.0 to 22.8‰, with an average of 4.6 ± 6.6‰). Lichens are on the average most depleted in ^{15}N (mean = −7.4 ± 6.4‰), whereas algae are most enriched in ^{15}N (10.0 ± 3.3‰). The broad range of nitrogen isotope compositions suggest that the N source for these Antarctic terrestrial plants is spatially much variable, with the local presence of seabird colonies being particularly significant.

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Introduction

The ice-free regions of maritime Antarctic are richly vegetated by lower plants such as lichens and mosses, forming important ecological components. Due to recent warming in this region, it is expected that the vegetation cover expands in newly exposed areas uncovered by glacier retreat (Convey and Smith 2006). Especially, many Antarctic plants grow in sites enriched by nitrogenous compounds derived from populations of seabirds (Smith 1995; Hovenden and Seppelt 1995). Because current environmental changes taking place in the maritime Antarctic may significantly alter ecosystem processes, it is important to understand the natural variation of their structure and function. Also, the terrestrial vegetation cover may influence soil-forming processes in the active layer, although the present soil-forming processes in the Antarctic region are very slow due to lower temperatures (e.g., Lee et al. 2004).

Although carbon and nitrogen techniques have been applied to a variety of terrestrial ecosystems (Nadelhoffer and Fry 1994; Högberg 1997; Unkovich et al. 2001; Asada et al. 2005), research on plant ^{13}C and ^{15}N abundance in maritime Antarctica is limited. Carbon isotope compositions of Antarctic terrestrial plants were first reported by Galimov (2000), who concluded that the variation in carbon isotope composition was species-controlled, rather than a result of variations in environmental factors. Here, we report more carbon isotope compositions of Antarctic terrestrial plants to test this hypothesis.

Due to the remote geographic position, the Antarctica is far from any major anthropogenic atmospheric inputs of nitrogen, which is in contrast to areas in the Northern Hemisphere where significant quantities of nitrogen are deposited as a result of human activities (Schulze 1989; Pearson and Stewart 1993). Thus, changes in Antarctic plant δ^{15}N values are expected to reflect the result of changes in the combination of natural nitrogen sources (Emmerton et al. 2001a, b). Growth of Arctic plants is thought to be limited by the low availability of nitrogen (Atkin 1996). However, the Antarctic region is exposed to substantial nitrogen inputs as the breeding ground for seals, penguins and other seabirds (e.g., Croxall et al. 2002; Weimerskirch et al. 2003; Huiskes et al. 2006; Bokhorst et al. 2007; Smykla et al. 2007). These animals deposit large quantities of excrement onto the ice-free coastal regions.

Nitrogen in the excrement of seabirds is rapidly mineralized, releasing ammonia gas (Lindeboom 1984; Mizutani et al. 1986). Previous studies on the subantarctic islands suggest that much of this ammonia is blown away and that the remaining soil inorganic nitrogen is washed out to sea (Gillham 1961; Smith 1978). However, other evidence suggests that animal-derived nitrogen is redistributed, providing a large source of nitrogen for terrestrial and marine plant life (Jenkin 1975; Lindeboom 1984; Greenfield 1992; Bokhorst et al. 2007; Smykla et al. 2007). Other studies have demonstrated that seabird guano and soil associated with their colonies are enriched in ^{15}N, with δ^{15}N values of between 6 and 26‰ (Wada et al. 1981; Mizutani and Wada 1988; Cocks et al. 1998; Wainright et al. 1998). Moreover, algae growing in the seabird and penguin colonies have δ^{15}N values between 15 and 31‰ (Wada et al. 1981; Mizutani and Wada 1988). The strong ^{15}N enrichment of avian-derived nitrogen suggests that its distinct isotopic signature could be used to determine the extent of animal-derived nitrogen inputs for plant nitrogen nutrition.

This paper reports natural abundances of ^{13}C and ^{15}N in a suite of mosses, lichens, liverworts, freshwater algae and grasses from snow-free areas on the Barton Peninsula of King George Island, South Shetland Islands, maritime Antarctic (Fig. 1) for database of terrestrial ecosystems. Seabird colonies are present on the Barton Peninsula.

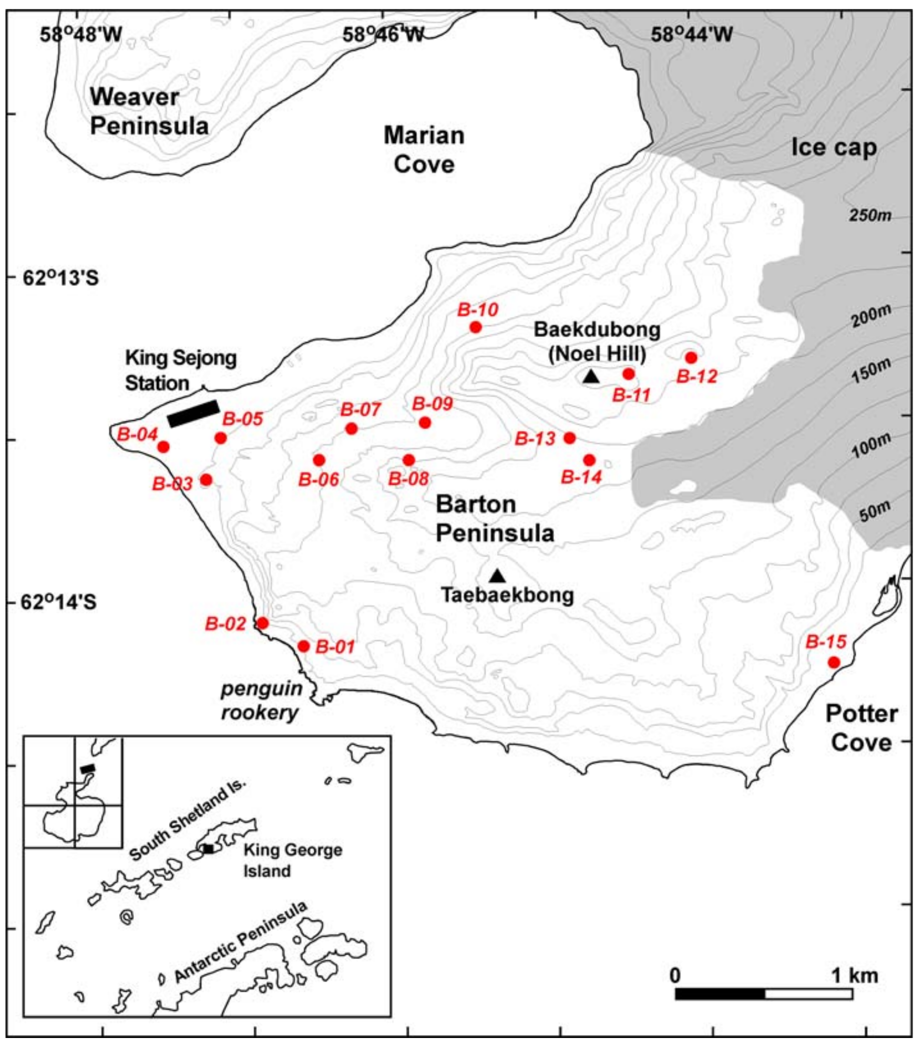

Fig. 1 Map of the Barton Peninsula, King George Island showing locations of the sampling sites (B numbers). The *insets* show location of the Barton Peninsula on King George Island and in the Antarctic

Certain Antarctic terrestrial plant species show variation in the C and N stable isotope ratios depending on sources and pathways of N and changes in the water availability (Huiskes et al. 2006). We want to show applicability of this hypothesis to Barton Peninsula terrestrial ecosystems. Understanding of ^{13}C and ^{15}N abundances in mosses and lichens could be useful for carbon and nitrogen cycles as they are dominant components of Antarctic vegetation and can effectively retain atmospheric-deposited nitrogen.

Materials and methods

Study area

The South Shetland Islands, located off the Antarctic Peninsula (Fig. 1), are calc-alkaline island arcs, separated from the Antarctic Peninsula by a young marginal basin, the Bransfield Strait. King George Island, the largest island in the South Shetland archipelago, is situated in the middle of the South Shetland Islands. The study area, the Barton Peninsula, is located in the southwestern part of King George Island (Fig. 1). Most of King George Island is covered with glaciers and outcrops are exposed only along the shorelines in restricted areas.

King George Island has a cold oceanic climate, characteristic of maritime Antarctica. Meteorological data of the study area recorded at the King Sejong Station of Korea for 9 years (1988–1996) show an average annual temperature of −1.8°C, relative humidity of 89%, precipitation of 437.6 mm, and wind velocity of 7.9 m/s, with major directions of northwest and southwest (Lee et al. 1997). The climate is relatively warm and humid supporting a substantial bryophyte flora including mosses and liverworts, lichens, and some freshwater algae. Bryophytes predominate in moister and more sheltered habitats, while lichens in more arid and exposed rocky habitats (Kim et al. 2007). A vascular plant newly colonized around the Barton Peninsula, *Deschampsia antarctica*, first reported by Kim and Chung (2004), grows on the stable and well-drained substrate (Kim et al. 2007).

The Barton Peninsula has a rugged topography with a wide and gentle slope in the central belt having elevations of 90–180 m above sea level. About 50% of the Barton Peninsula is covered by vegetation (Kim et al. 2007). Coastal zones and depressions on rock terraces on gentle slopes are wet for prolonged periods due to stagnating melt water, whereas highland areas are well drained. Lichens grow on rocky substrates or on scree. The Chottaebawi area on the southern coast of the Barton Peninsula is one site of important penguin colonies in the maritime Antarctic region. This site has large concentration of gentoo (*Pygoscelis papua*) and chinstrap (*Pygoscelis antarctica*) penguins. Also, the cape area near the King Sejong Station is abundantly populated by flying seabirds like skua. On the southeastern coast (SW of B-15 in Fig. 1) marine animals like Antarctic fur and elephant seals are frequented.

Field sampling and analytical methods

Twenty-two moss, 24 lichen, 3 liverwort, 3 freshwater alga, and 5 grass specimens were collected at many sites in the snow-free areas of the Barton Peninsula (Fig. 1). The collected species represent each individual, but some samples contain mixed species. Collections were performed in January and February 2006. Among sampling sites, B-01 and B-02 are very close to the active penguin rookeries, B-04 to the abundant skua population area, and B-15 to fur and elephant seals resting place.

Plant samples (one individual plant at each site) were ultrasonically cleaned, oven-dried at 60°C and then ground to a fine powder in an agate mortar. When samples contain mixed species, each species was carefully separated. Elemental (%TOC and %N) and isotopic ratios of carbon and nitrogen ($\delta^{13}C$ and $\delta^{15}N$) were analyzed using an IsoPrime continuous gas flow stable isotope mass spectrometer made by Micromass coupled to a CN analyzer (NA Series 2, CE Instruments) at the National Instrumentation Center for Environmental Management, Seoul National University. Stable isotope abundances were expressed in δ-notation as the deviation from standards in parts per thousand (‰):

$$\delta X = [(R_{\mathrm{sample}}/R_{\mathrm{standard}}) - 1] \times 1000$$

where X is ^{13}C or ^{15}N and R is the corresponding ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$. The R_{standard} values were based on the PeeDee Belemnite (PDB) for ^{13}C and atmospheric N_2 for ^{15}N. The analytical precision of the isotopic measurements of multiple replicate analyses was <0.1‰ for carbon and <0.2‰ for nitrogen.

Results

Total organic carbon (TOC) and total nitrogen (TN)

TOC and TN contents of Barton Peninsula plants range from 18.5 to 47.1% and from 0.2 to 4.6%, respectively (Table 1). On average lichens contain the highest amount of TOC, but the smallest amount of TN, resulting in the highest value of C/N. On the contrary, algae contain least TOC but most TN, resulting in the lowest value of C/N. Especially C/N values of mosses and lichens are highly variable due to large fluctuations in the nitrogen content. Among mosses, *Sanionia georgico-uncinata* and *Polytrichum strictum* growing at sites located near the active penguin colony (B-01 and B-02) and skua population sites

Table 1 Values of total organic carbon (TOC), total nitrogen (TN), C/N ratio, isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N) for particular species (exact values from each sampling site) and groups of taxa (mean ± SD)

Species	TOC (%)	δ^{13}C (‰)	TN (%)	δ^{15}N (‰)	C/N ratio	Site	Distance from the nearest coast (m)	Distance from animal influence (m)
Mosses ($n = 22$)								
Andreaea regularis	33.34	−24.7	0.71	−2.3	46.8	B-06	460	
Andreaea regularis	39.18	−22.9	1.03	2.4	38.0	B-03	140	250 (SK)
Andreaea regularis	38.33	−23.9	0.92	2.2	41.8	B-03	140	250 (SK)
Andreaea regularis	37.94	−25.4	0.48	1.6	79.4	B-03	140	250 (SK)
Bartramia patens	30.06	−28.0	0.69	4.0	43.3	B-07	490	
Bryum pseudotriquetrum	34.09	−25.1	1.76	6.4	19.4	B-15	60	200 (SB, SM)
Bryum pseudotriquetrum	40.00	−24.7	2.14	12.2	18.7	B-03	140	250 (SK)
Bryum pseudotriquetrum	44.61	−25.6	1.86	3.8	24.0	B-03	140	250 (SK)
Chorisodontium aciphylum	39.53	−24.7	0.58	12.0	68.4	B-02	55	500 (PR)
Polytrichastrum alpium	37.79	−27.3	0.98	2.9	38.4	B-01	85	250 (PR)
Polytrichum strictum	41.37	−28.2	0.93	-9.0	44.3	B-10	430	
Polytrichum strictum	42.84	−26.4	1.54	22.8	27.9	B-02	55	500 (PR)
Polytrichum strictum	31.64	−26.0	2.08	14.2	15.2	B-02	55	500 (PR)
Polytrichum strictum	42.72	−27.0	0.61	1.3	70.3	B-03	140	250 (SK)
Sanionia georgico-uncinata	31.81	−24.4	0.51	−2.6	62.7	B-14	1,300	
Sanionia georgico-uncinata	28.78	−27.9	1.14	5.4	25.3	B-03	140	250 (SK)
Sanionia georgico-uncinata	18.54	−27.9	0.41	−1.0	44.8	B-03	140	250 (SK)
Sanionia georgico-uncinata	35.37	−25.6	1.31	5.7	26.9	B-01	85	250 (PR)
Sanionia georgico-uncinata	40.21	−24.0	1.40	9.5	28.8	B-01	85	250 (PR)
Sanionia georgico-uncinata	37.24	−26.6	1.23	3.1	30.2	B-01	85	250 (PR)
Sanionia georgico-uncinata	34.93	−27.9	0.57	2.5	61.3	B-07	490	
Sanionia georgico-uncinata	38.83	−25.1	1.32	4.7	29.4	B-03	140	250 (SK)
Mean(± SD)	36.32 ± 5.82	−25.9 ± 1.6	1.10 ± 0.53	4.6 ± 6.6	40.2 ± 18.2			
Lichens ($n = 24$)								
Cladonia cf. gracilis	43.41	−26.4	0.62	1.9	69.7	B-01	85	250 (PR)
Himantormia lugubris	40.64	−24.7	0.35	−13.5	116.8	B-11	860	
Himantormia lugubris	41.61	−20.1	0.36	−10.6	115.6	B-10	430	
Himantormia lugubris	38.40	−24.7	0.30	−10.4	128.0	B-08	690	
Ochrolechia frigida	26.78	−25.6	0.64	0.7	41.9	B-05	250	250 (SK)
Ramalina terebrata	38.09	−22.4	0.73	−3.0	52.4	B-02	55	500 (PR)
Sphaerophorus globosus	39.03	−25.3	0.24	0.6	160.0	B-03	140	250 (SK)
Sphaerophorus globosus	34.37	−26.8	0.47	1.1	72.7	B-05	250	250 (SK)
Stereocaulon alpinum	47.11	−27.0	0.69	1.0	67.9	B-04	85	100 (SK)
Stereocaulon alpinum	36.59	−27.1	0.69	−0.7	53.4	B-03	140	250 (SK)
Stereocaulon alpinum	42.25	−29.0	0.56	0.3	75.7	B-03	140	250 (SK)
Stereocaulon alpinum	21.48	−28.5	0.64	0.5	33.5	B-05	250	250 (SK)
Usnea antarctica	39.58	−22.6	0.29	−15.3	136.0	B-09	540	
Usnea antarctica	42.61	−20.3	0.21	−7.8	206.9	B-07	490	
Usnea antarctica	40.42	−21.4	0.25	−13.0	164.3	B-13	1,200	
Usnea antarctica	44.26	−21.4	0.24	−11.4	185.2	B-12	940	
Usnea antarctica	42.95	−20.0	0.27	−13.4	160.8	B-12	940	
Usnea antarctica	41.35	−21.8	0.33	−11.2	125.3	B-09	540	
Usnea antarctica	40.79	−20.0	0.35	−10.1	115.2	B-03	140	250 (SK)
Usnea aurantiaco-atra	43.65	−21.9	0.29	−14.5	151.6	B-09	540	
Usnea aurantiaco-atra	46.28	−22.6	0.43	−7.3	107.6	B-07	490	

Table 1 continued

Species	TOC (%)	$\delta^{13}C$ (‰)	TN (%)	$\delta^{15}N$ (‰)	C/N ratio	Site	Distance from the nearest coast (m)	Distance from animal influence (m)
Usnea aurantiaco-atra	41.97	−22.6	0.32	−13.8	129.5	B-12	940	
Usnea aurantiaco-atra	44.16	−22.2	0.39	−13.7	113.8	B-12	940	
Usnea aurantiaco-atra	40.39	−22.3	0.34	−13.2	119.2	B-03	140	250 (SK)
Mean(± SD)	39.92 ± 5.71	−23.6 ± 2.8	0.42 ± 0.17	−7.4 ± 6.4	112.6 ± 46.4			
Liverworts ($n = 3$)								
Cephalozia badia	37.18	−25.8	0.64	0.8	57.9	B-03	140	250 (SK)
Cephaloziella varians	32.89	−26.8	0.61	1.2	53.8	B-07	490	
Cephaloziella varians	42.17	−26.3	0.79	−2.9	53.2	B-03	140	250 (SK)
Mean(± SD)	37.41 ± 4.65	−26.3 ± 0.5	0.68 ± 0.10	−0.3 ± 2.3	55.0 ± 2.5			
Algae ($n = 3$)								
Prasiola crispa	30.78	−27.7	4.55	6.4	6.8	B-01	85	250 (PR)
Prasiola crispa	32.15	−25.3	3.51	12.8	9.2	B-04	85	100 (SK)
Prasiola crispa	36.63	−25.9	4.03	10.8	9.1	B-01	85	250 (PR)
Mean(± SD)	33.19 ± 3.06	−26.3 ± 1.2	4.03 ± 0.52	10.0 ± 3.3	8.3 ± 1.4			
Grasses ($n = 5$)								
Deschampsia antarctica	36.92	−28.6	1.49	4.2	24.8	B-04	85	100 (SK)
Deschampsia antarctica	36.52	−24.9	2.34	3.2	15.6	B-15	60	200 (SB, SM)
Deschampsia antarctica	38.99	−24.6	1.96	0.4	19.9	B-15	60	200 (SB, SM)
Deschampsia antarctica	41.26	−25.2	2.10	1.7	19.7	B-15	60	200 (SB, SM)
Deschampsia antarctica	41.73	−24.6	1.64	0.2	25.5	B-15	60	200 (SB, SM)
Mean(± SD)	39.08 ± 2.40	−25.6 ± 1.7	1.90 ± 0.34	1.9 ± 1.7	21.1 ± 4.1			

For location of sampling sites see Fig. 1

PR penguin rookery, *SK* skua, *SB* seabird, *SM* sea mammal

(B-03) have higher nitrogen content than the same species collected from other sites, resulting in lower C/N ratios.

Carbon isotope

The mean $\delta^{13}C$ values vary from −26.3 to −23.6‰ among different groups of taxa. The $\delta^{13}C$ values of lichens range most widely from −29.0‰ (*Stereocaulon alpinum*) to −20.0‰ (*Usnea antarctica*), yet the average $\delta^{13}C$ value is the highest among the Barton Peninsula plants (Fig. 2). Among lichens *U. antarctica* and *U. aurantiaco-atra* are most ^{13}C-enriched and show a relatively narrow range of $\delta^{13}C$ values from −22.6 to −20.0‰ (Table 1). The average $\delta^{13}C$ values of mosses, liverworts, algae, and grasses are slightly more negative than that of lichens. The range of moss $\delta^{13}C$ values is from −28.2‰ (*Polytrichum strictum*) to −22.9‰ (*Andreaea regularis*) and of liverwort $\delta^{13}C$ values from −26.8 to −25.8‰. *Prasiola crispa*, the only algal species collected in this study, varies in $\delta^{13}C$ values from −27.7 to −25.3‰. The variation in $^{13}C/^{12}C$ ratios between individual liverwort and algal species is much less than those for lichens and mosses. The grass species, *Deschampsia antarctica*, shows $\delta^{13}C$ values from −28.6 to −24.6‰.

Nitrogen isotope

Compared to the rather narrow range in $\delta^{13}C$ values, the nitrogen isotopic compositions of Barton Peninsula plants vary between a wider span (−15.3 to 22.8‰; Fig. 2). The $\delta^{15}N$ values of moss samples range widest (−9.0 to 22.8‰). Lichens are on average most depleted in ^{15}N, whereas algae are most enriched (10.0 ± 3.3‰). *Usnea antarctica*, *U. aurantiaco-atra,* and *Himantormia lugubris*, the most dominant lichens in the Barton Peninsula, are more depleted in ^{15}N than other lichens (Fig. 3). The $\delta^{15}N$ values of liverworts and grasses are narrowly distributed. The most ^{15}N-depleted lichens are also characterized by low nitrogen contents (Fig. 4). In contrast, the algal samples are characterized by their high ^{15}N values and high nitrogen content (Fig. 4).

Discussion

Terrestrial plants normally have relatively high C/N ratios of >12 (Prahl et al. 1980) because it is composed predominantly of lignin and cellulose, which are nitrogen

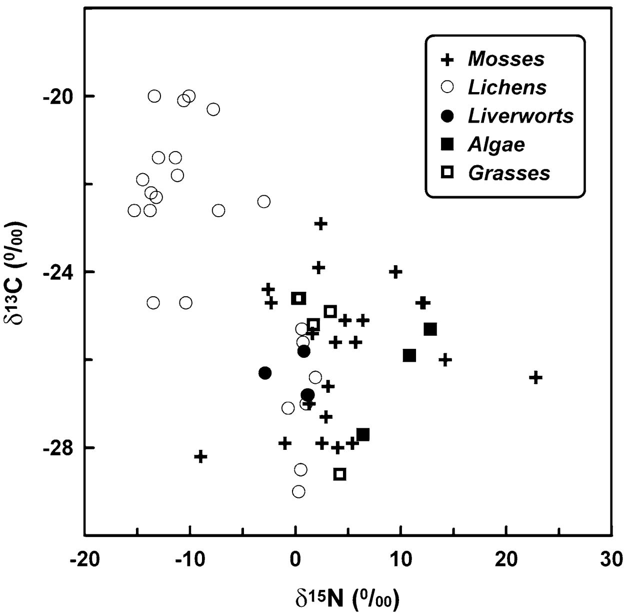

Fig. 2 Plot of all isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) values illustrating differences among particular groups of taxa

poor. Most species of mosses, lichens and liverworts have C/N ratios larger than 33 and grasses have a C/N ratio larger than 15, which fits the terrestrial vegetation characteristic. The algal species has a C/N ratio less than 10, typical for algae both of marine and freshwater (Meyers 1994; Tyson 1995), whereas $\delta^{13}C$ values fall within the typical range for freshwater alga (c.f. Schidlowski et al. 1983; Meyers 1994).

The $\delta^{13}C$ values of Barton Peninsula plants are typical of terrestrial plants that use the C_3 photosynthetic pathway in lower latitudes (Ehleringer et al. 1993). The observed $\delta^{13}C$ values of this study are very similar to those of Galimov (2000) reported from the similar maritime Antarctic region.

The most interesting feature in the distribution pattern of $\delta^{13}C$ values is isotope specificity of the species. Particular species within each plant taxonomic group seem to have different $\delta^{13}C$ values and different species at the same sampling location seem to have also different $\delta^{13}C$ values, signifying species control on $\delta^{13}C$ values. This conclusion was noted by Galimov (2000). Such carbon isotope specificity of the species can also be accounted for by different water-use efficiency (Farquhar et al. 1982), suggesting that lichens show the largest difference in water-use efficiency among species. However, on average lichens show the highest water-use efficiency among the Barton Peninsula plants, which fits with their habitat. Although sampling was not done following a gradient of nutrient or water availability, *Usnea* and *Himantormia* species collected in more inland and higher altitude locations (plotted in the upper left of Fig. 2) have higher $\delta^{13}C$ and lower $\delta^{15}N$ values than other lichens collected in the coastal region (Table 1), which fits with the water availability hypothesis corroborated by Huiskes et al. (2006). Among mosses, *Andreaea* shows the highest $\delta^{13}C$ values, as they are very common in dry exposed rocks of relatively high altitude (Kim et al. 2007).

Figure 5 shows ranges of carbon isotope composition of different taxonomic groups of the Antarctic terrestrial plants by combining the data of this study, Galimov (2000), Huiskes et al. (2006), and Park et al. (2007). The $\delta^{13}C$ values and ranges of moss and lichen species are very similar to those of the present study, except for the addition of ^{13}C-enriched *Drepanocladus sp.* (−21.3‰) for mosses, and *Umbillicaria antarctica* (−18.8‰) and *Buellia sp.* (−19.5‰) for lichens (Galimov 2000), thus extending carbon isotope composition range to slightly heavier $\delta^{13}C$ side. The most significant change in ^{13}C abundance is observed in algae. Although being the same species, *Prasiola crispa* reported by Galimov (2000)

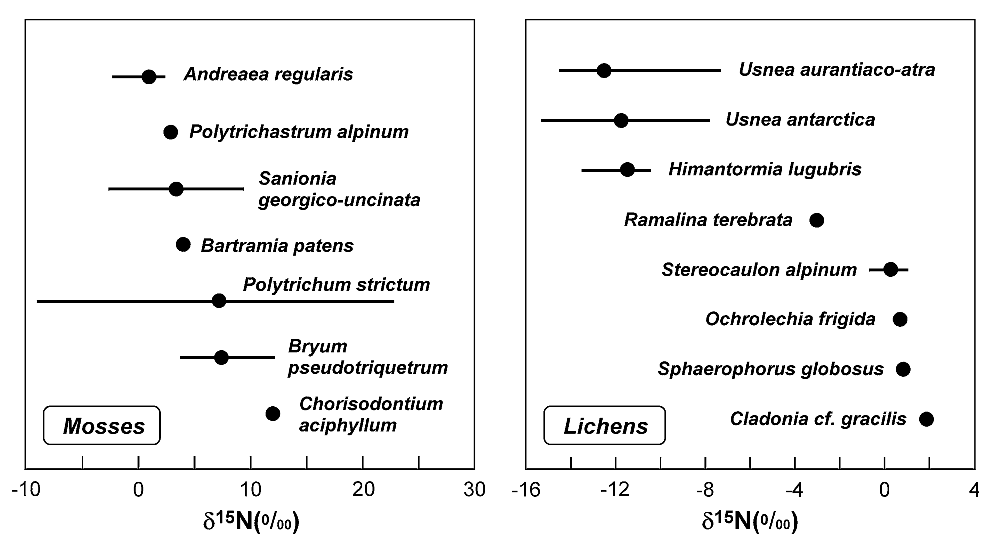

Fig. 3 Nitrogen isotope ($\delta^{15}N$) values for particular species of mosses and lichens, range (*solid line*) and average values (*dot*)

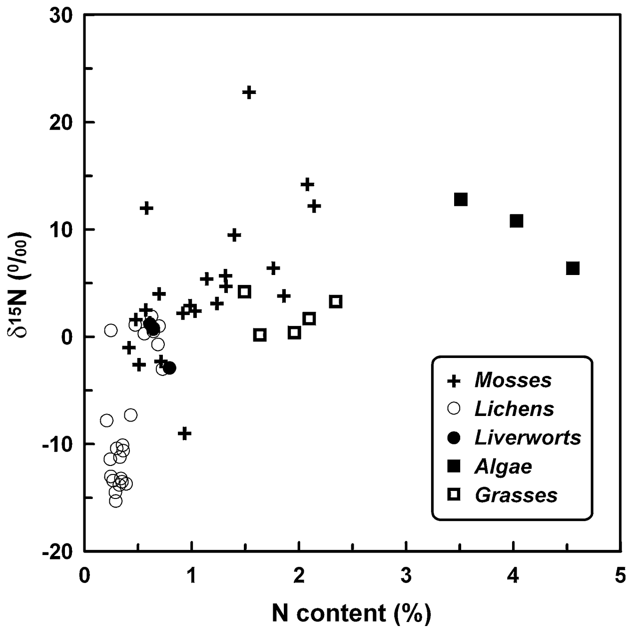

Fig. 4 Plot of all total nitrogen (N) and nitrogen isotope (δ^{15}N) values illustrating differences among particular groups of taxa

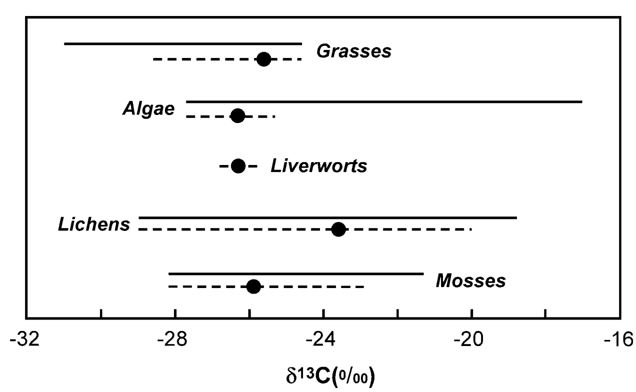

Fig. 5 Carbon isotope (δ^{13}C) values for particular groups of taxa, range (*lines*) and average values (*dots*) of maritime Antarctic. *Broken lines and dots* present the authors original data. Other data are from literature (Galimov 2000; Huiskes et al. 2006, and Park et al. 2007)

shows variations of δ^{13}C values from −25.6 to −19.8‰ ($n = 7$) with an average of −22.1 ± 1.9‰ and that reported by Huiskes et al. (2006) from −23 to −17‰ ($n = 22$), falling beyond the heavier end of the present study (−25.3‰). Such higher δ^{13}C values of algae reported by Galimov (2000) and Huiskes et al. (2006) are heavier than the typical range of freshwater algae in C_3-dominated environments (e.g. Schidlowski et al. 1983; Meyers 1994), but fall within the range of marine algae (e.g. Haines 1976; Meyers 1994). Considering the finding of Huiskes et al. (2006) that *P. crispa* shows higher δ^{13}C values in coastal and wet habitats than that in more inland and drier habitats, terrestrial algae collected in the Barton Peninsula may represent the driest habitat among the Antarctic ecosystems so far studied. In fact, algae samples for this study were collected from the well-drained meltwater gullies. In compiled data of mosses and lichens the isotope specificity of the species is also well displayed in Fig. 6, indicating that δ^{13}C variations in different species seem to be due solely to individual plant physiology (water-use efficiency) and biochemistry, probably related to water availability.

The wide range of δ^{15}N values (>38‰) in this study reflects the influence of uptake of animal-derived nitrogen (Erskine et al. 1998). Mosses show the large variation of δ^{15}N values ($\Delta\delta^{15}N = 32$‰). In the Barton Peninsula mosses commonly grow in and close proximity to the penguin rookery. Mosses take up all its nutrients by rhizoids from the substrate and via their aerial parts from runoff water and aerosol N, thus the chemical composition of mosses seems to be influenced significantly by the nature of substrate on which it grows (de Caritat et al. 2001). The gentoo penguin guano on King George Island has mean δ^{15}N value of 12.5‰ (Liu et al. 2006). All moss samples but four have widely varying positive δ^{15}N values, which suggests that assimilation of ^{15}N-enriched, guano-derived nitrogen significantly influenced these moss species, like nitrogen sources commonly reported from terrestrial floras in other Antarctic regions (Cocks et al. 1998; Greenfield 1992; Huiskes et al. 2006; Bokhorst et al. 2007). Four moss samples having negative δ^{15}N signatures were collected distant from the penguin rookery and seem to reflect the δ^{15}N of the isotopically depleted ammonia source.

On the contrary, lichens are characterized by strongly depleted in ^{15}N. Especially, *Usnea antarctica*, *U. aurantiaco-atra*, and *Himantormia lugubris* grow at wind exposed areas, consistent with the vegetation zone least affected by penguin impact (Smykla et al. 2007). No trend is observed in δ^{15}N values for these lichen species with distance from the coast, which suggests that these lichen species rely on precipitation as a nitrogen source. Other lichen species collected in the coastal zone show δ^{15}N values close to 0‰, suggestive of more marine influence than *Usnea* and *Himantormia* species upland (Fig. 4). In addition, *Streocaulon alpinum*, the only lichen with cyanobacteria in this study, also differed strongly in its N signature (close to 0‰) and in low C/N ratio (<76).

Algae grow commonly along natural drainage lines. Highly enriched δ^{15}N values observed in algae reflect that the algae assimilated significant amounts of penguin guano-derived, ^{15}N-enriched soluble N such as ammonium. Flowering plants, *Deschampsia antarctica* have slightly positive δ^{15}N values from 0.2 to 4.2‰. These grasses were collected from the raised beach close to the modern beach where colonies of seabirds and marine animals are conspicuous nearby, suggesting that they were influenced by

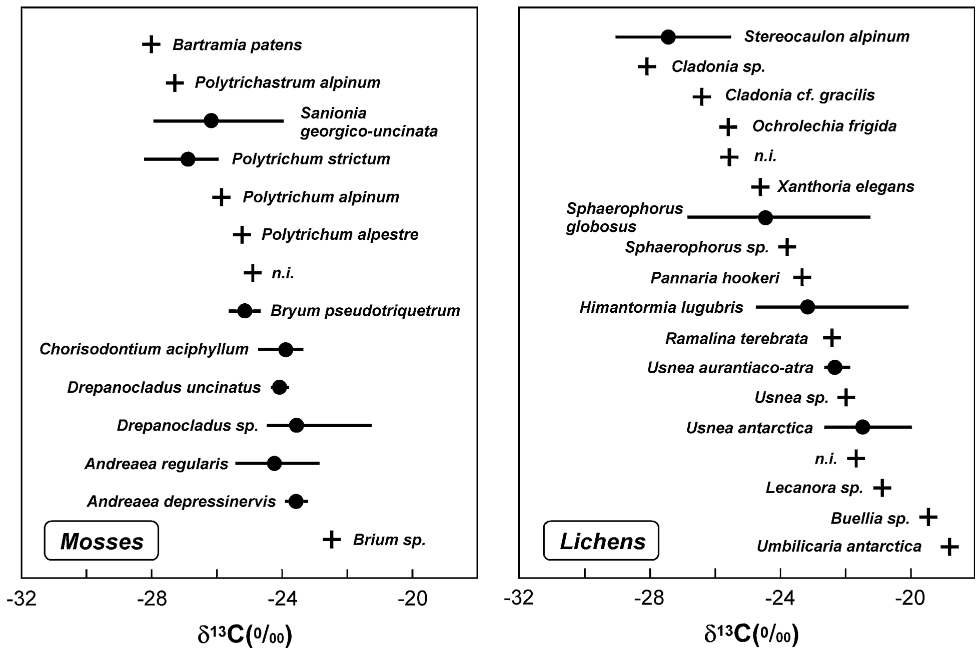

Fig. 6 Carbon isotope (δ^{13}C) values for particular species of mosses and lichens, range (*line*) and average values (*dot*). + denotes single value, *n.i.* unidentified species. Figure presents the authors original data combined with data from literature (Galimov 2000; Huiskes et al. 2006; Park et al. 2007)

animal-derived dissolved inorganic N via soil waters from these animal colonies.

Conclusions

The Antarctic terrestrial plants on King George Island, South Shetlands Islands, show species specificity of both carbon and nitrogen isotope compositions, probably due to differences in plant physiology and biochemistry. Among them lichens are most enriched in ^{13}C with the widest range ($\Delta\delta^{13}$C = 9‰), and most depleted in ^{15}N. Lichens in the coastal zone have lower δ^{13}C and higher δ^{15}N values compared to *Usnea* and *Himantormia* species distributed in more inland and upland locations, probably due to higher water availability and greater marine influence. Having moister habitats and more depleted ^{13}C concentrations than lichens, average δ^{13}C values of grasses, mosses, liverworts, and algae are similar at about −26‰. The δ^{15}N values of mosses range the widest ($\Delta\delta^{15}$N = 32‰), being most sensitive to the influence of seabird guano, as is for algae having enriched ^{15}N. The generally wide range of nitrogen stable isotope ratios of King George Island terrestrial plants ($\Delta\delta^{15}$N = 38‰) indicates that external mineral nitrogen inputs are spatially very variable because of the significant local influence of seabird colonies.

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