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Spectral characteristics of the Arctic ornithogenic tundra vegetation in Hornsund area, SW Spitsbergen

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Abstract: Solar radiation reflectance was analysed to characterize Arctic ornithogenic tundra developing in the vicinity of large breeding colony of Brunnich‘s guillemots *Uria lomvia* and kittiwakes *Rissa tridactyla* at the foot of Gnålberget cliff (Hornsund, SW Spitsbergen). Radiometric method was found to be a useful tool for studying structure and functioning of plant formations. We measured reflectance of four wavelengths: 554 nm (YG), 655 nm (RED), 870 nm (NIR) and 1650 nm (SWIR) at 10 plots situated along the transect running from the colony to the sea. Moreover, data of plant community character, species quantitative composition as well as total biomass were collected to relate these parameters with the spectral values. The results showed that radiometric data characterized vegetation well enough to recognize the same plant communities on the basis of spectral reflectance as distinguished with traditional phytosociological methods.

Key words: Arctic, Spitsbergen, ornithogenic tundra, radiometric characteristics, spectral reflectance.

Introduction

In relation to conventional research methods, radiometric analysis of vegetation is a relatively new, alternative and complementary technique. It seems to enable precise gathering of information concerning the structure and functioning of plant communities (Tucker 1980; Hobbs 1990; Behrens *et al.* 2004; Starks *et al.* 2006; Liu *et al.* 2007). As data collecting using this method is easy and fast, it is possible to gather large numbers of measurements, and consequently to follow current changes of the vegetation and to monitor biosphere on a large scale (Laidler and Treitz 2003; Fernández-Buces *et al.* 2006). It is also known that plant communities' analysis performed by means of spectral data confirms the results

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obtained for the classification based on floristically-phytosociological data (Hope *et al.* 1993; Strąg and Barcikowski 2002). Spectral response of each site is the sum of radiation reflections from particular plants. Thus, the places with similar species composition give similar spectral response what makes possible to distinguish them from other communities (Tucker and Thorsteinsson 1980; Trodd 1996).

There is a deep conviction about strong relationship between structural and functional parameters of vegetation, such as biomass and cover of plants, leaf area index and chlorophyll content, and its spectral characteristics (Tucker 1977; Yamada and Fujimura 1991; Calera *et al.* 2001; Laidler and Tretz 2003; Numata *et al.* 2003; Behrens *et al.* 2004; Schmidtlein 2005; Fernández-Buces *et al.* 2006; Harris 2008). Reflectance of various bands of radiation can be used for discriminating between live and dead aboveground plant biomass or for obtaining green plant cover (Lorenzen and Jensen 1988; Calera *et al.* 2001; Piekarczyk 2005; Liu *et al.* 2007).

Arctic seabirds, which feed at sea and breed on land in large colonies, play a crucial role in initiating and maintaining local concentration of plants and animals as well as in ecosystem functioning. For example, during one breeding season in Hornsund, SW Spitsbergen, little auks (*Alle alle*) deliver ~60 t dry mass of guano km^{-2} to the colony area, ~25 t km^{-2} to the circular flight zone around the colony and ~0.6 t km^{-2} to the tundra between the colony and sea (Stempniewicz 1990, 1992). As a result of considerable deposition of guano, as well as of various forms of organic matter (lost prey items, eggs, dead chicks, adults etc.), colonial seabirds contribute to increase of the primary and secondary production and species diversity, thus modifying nearby tundra plant communities (Stempniewicz 2005; Stempniewicz *et al.* 2007).

The aim of the study was to characterize Arctic ornithogenic tundra, i.e. plant communities developing in the vicinity of seabirds' colony, with radiometric data using four wavebands of the sunlight spectrum and vegetation index NDVI. The purpose of the analysis was to check whether vegetation diversity observed along the transect, which was earlier classified using conventional phytosociological methods, could be described with radiometric parameters. We also analysed relationships between spectral response of the vegetation and its dry aboveground biomass.

Study area

The study was conducted in the ornithogenic tundra developing near breeding colony of Brunnich's guillemots *Uria lomvia* and kittiwakes *Rissa tridactyla* at the foot of Gnålberget cliff (77°01'N 15°52'E), on the north coast of Hornsund fjord (South-West Spitsbergen). The area of the study extended between the cliff where the colony was situated and the seashore (ca. 500 m from the cliff). Tundra slope

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inclination decreased along with the distance from the colony (Spearman's correlation coefficient, $r_S = -0.76$; $p < 0.05$; $n = 10$) starting with 40–50° directly under the cliff side and ending with a flat plain on the shore.

Exceptionally rich and lush vegetation occurring in the study area is characteristic of completely formed Arctic phytocoenoses developing below the well fertilized bird-cliffs (Rønning 1996). They consist of a mixture of herbs, grasses and mosses forming continuous thick mats. Using classical phytosociological methods, five separate plant communities were distinguished within the transect (Table 1).

Materials and methods

The study was conducted at the turn of July and August in 2005 and 2006. Ten sample plots (160×160 cm) were situated along the transect in the ascending distances from the colony (Table 1). Thus, there were more sample plots in the vicinity of the colony, where the greatest variation in vegetation was observed (beside the area directly under the cliff), than in the coastal area, more distant from the cliff and less diversified. All the measurements were taken within the study plots.

Measurements of plant species composition and biomass. — A list of vascular plant and moss species, together with their proportional cover (%), as a measure of abundance, was prepared within each plot. Five samples of vegetation (20×20 cm) were collected along a diagonal of each sample plot in order to asses live biomass. Only the aboveground parts of plants and mosses were analysed. The samples were divided into particular layers (vascular plants and mosses separately), dried to a stable weight and subsequently weighed [gDW]. Total biomass from all samples of the study plots were extrapolated to 1 m^2.

Measurements of reflectance. — Radiometric measurements of vegetation were performed by means of four-channel radiometer constructed in the Space Research Centre, Polish Academy of Science in Warsaw, specially for this kind of purposes. There were four spectral channels on the head of the appliance, equipped with narrow-band filters, which selected solar radiation reflectance in the following wavelengths:
- channel 1: $\lambda = 554$ nm, yellow-green radiation (YG);
- channel 2: $\lambda = 655$ nm, red radiation (RED);
- channel 3: $\lambda = 870$ nm, near infrared radiation (NIR);
- channel 4: $\lambda = 1650$ nm, short wave infrared radiation (SWIR).

Filter half-width amounted $\Delta\lambda = 10–14$, and angle field of view amounted $2u = 14°$.

In addition, there was a reference channel on the head of radiometer, equipped with a ground glass, a diffuser and a wide band filter $\Delta\lambda = 550–870$ nm, recording direct solar radiation (insolation measurement). Because of changes in insolation conditions during proper measurements of radiation reflected from the studied surface, the absolute values given by the appliance were converted into proportional values of reflected radiation in relation to incident radiation under the given conditions. It was possible thanks to calibration measurements (control) of radiation reflected from a white screen covered with barium sulphate $BaSO_4$, which is a chemical standard of absolute whiteness. The value of radiation reflection from a white screen was treated as 100% value of radiation reflection reaching a given surface.

Measurements of reflectance were recorded in 5 points (3 repetitions in each) along a diagonal of each sample plot, perpendicularly to the studied surface, from the height of about 1m. In total, 150 measurements were obtained from the whole transect.

To analyse potential information included in plant spectral reflectance and to minimize influence of disturbances caused by soil background and atmospheric factors, we calculated the widely used Normalized Difference Vegetation Index (NDVI) (Ray 1994; Laidler and Treitz 2003). NDVI is based on the ratios of reflection difference between RED and NIR radiation:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

It is useful mainly because it normalizes the difference between maximum absorption within the red wavelengths and peak reflectance in the near infrared. This relationship between RED and NIR wavelengths provides the most information regarding vegetation properties, like health, stress level, green biomass and chlorophyll content. It is sensitive to vegetation changes, especially to plant cover, and reaches the values from -1 to +1 (Strąg and Barcikowski 2002; Laidler and Treitz 2003).

Statistical analysis. — The results were processed by use of STATISTICA 6.0 package for the Spearman rank correlation and Kruskal-Wallis tests (non-parametric because of biased distribution and quite low number of sample plots), Dunn'sTest 8.01 for *post-hoc* Dunn's test and CANOCO 4.5 package for ordinations. We used numerical ordination method (indirect gradient analysis) (CANOCO 4.5; ter Braak and Šmilauer 2002) for the purpose of identifying total variability of vegetation and radiometric data. Detrended Correspondence Analysis (DCA) was used for the data of plant species composition and Principal Component Analysis (PCA) for the radiometric measurements, because of different lengths of gradient (3.523 for plants species and 0.132 for radiometry).

Results

Using standard phytosociological methods, five tundra communities were distinguished on the study transect between the colony and seashore (Wojtuń, unpubl.; Table 1). They were characterised by high total vegetation cover, ranging between

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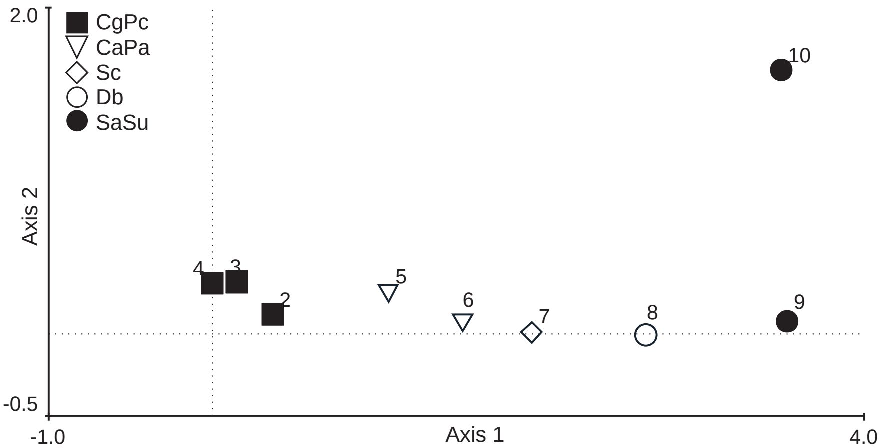

Fig. 1. Sample plots ordination (DCA) on the basis of plant species composition with distinct community types plotted: CgPc – *Cochlearia groenlandica–Prasiola crispa*, CaPa – *Cerastium arcticum–Poa alpina*, Sc – *Saxifraga caespitosa*, Db – *Deschampsia borealis*, SoSu – *Saxifraga oppositifolia–Sanionia uncinata*. Numbers reflect sample plots order along the transect.

95% and 100%. The exception was the first plot with only 30% cover of plants. This area, situated directly under the colony, was exposed to mechanical damages because of rocks falling off the fragile cliff as well as lost nest material, eggshells, food items etc. For this reason we excluded the plot from further analyses.

In the case of plant species composition, the main gradient that differentiated the data running along the first axis corresponded with the sequence of sample plots and distinguished communities along the transect (Fig. 1) and significantly

Table 1

Location of sample plots along the transect and their phytosociological description (classification according to Wojtuń unpubl.)

Plot number	Distance from the colony [m]	Community type
1*)	0.0	*Cochlearia groenlandica–Prasiola crispa* (CgPc)
2	6.0	
3	15.0	
4	28.5	
5	48.8	*Cerastium arcticum–Poa alpine* (CaPa)
6	79.1	
7	124.7	*Saxifraga caespitosa* (Sa)
8	193.0	*Deschampsia borealis* (Db)
9	295.5	*Saxifraga oppositifolia–Sanionia uncinata* (SoSu)
10	449.3	

1*) – sample plot excluded from further analyses because of mechanical damage caused by stones falling from the cliff resulting in incomparably low total cover of vegetation (30%).

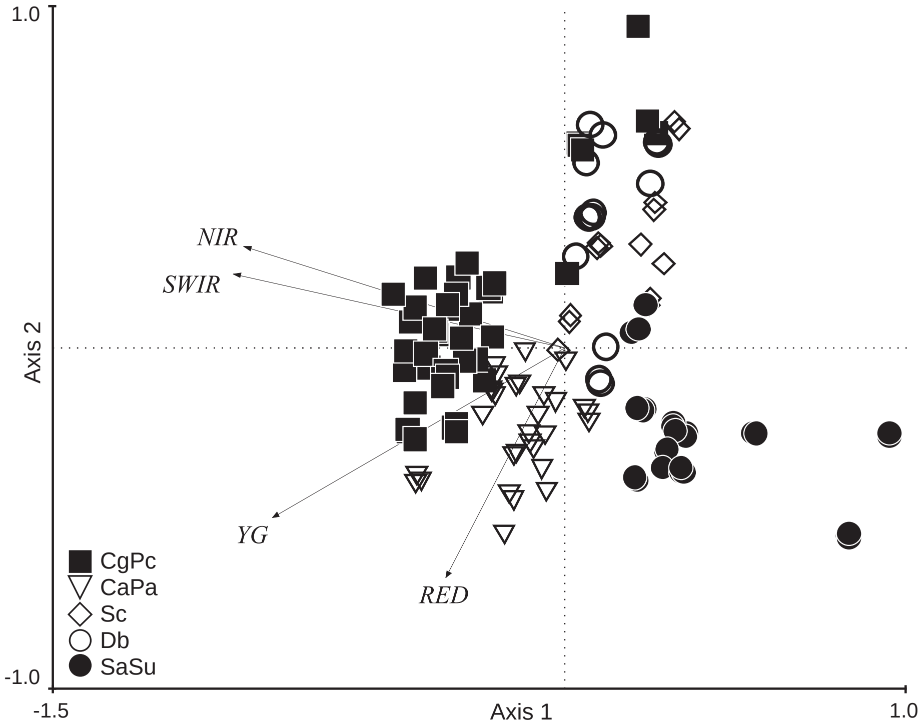

Fig. 2. Radiometric measurements ordination (PCA) on the basis of reflectance values for bands: YG, RED, NIR and SWIR with distinct community types plotted: CgPc – *Cochlearia groenlandica–Prasiola crispa*, CaPa – *Cerastium arcticum–Poa alpina*, Sc – *Saxifraga caespitosa*, Db – *Deschampsia borealis*, SoSu – *Saxifraga oppositifolia–Sanionia uncinata*.

correlated with the plot distance from the colony ($r_S = 0.92$, p <0.001, n = 9). The first axis explained 43.5% of the total variability of samples, while the second axis only 7.7%.

The first axis of PCA diagram (Fig. 2) based on spectral reflectance values for the four studied wavelengths: YG, RED, NIR and SWIR explained 82.2% and the second axis 14.3% of the total variability and sample scores for the first axis also correlated positively with the distance of the particular plot from the colony (r_S = 0.78, p <0.001, n = 134). Moreover, plant communities distinguished by phytosociological methods were distinctly visible on the diagram as separate groups of samples, even though some of the samples mixed with those belonging to another community. These differences in spectral reflectance between particular plant communities were statistically significant (Kruskal-Wallis test – Table 2, *post-hoc* Dunn's test performed for each reflectance channel and NDVI index individually; Figs 3 and 4). The most distinct communities were *Cochlearia groenlandica–Prasiola crispa* which was situated closest to the colony and *Saxifraga oppositifolia–Sanionia uncinata*, the most distant from seabirds' nests, closest to the sea. Both CgPc and SoSu differed from the most of remaining communities in the

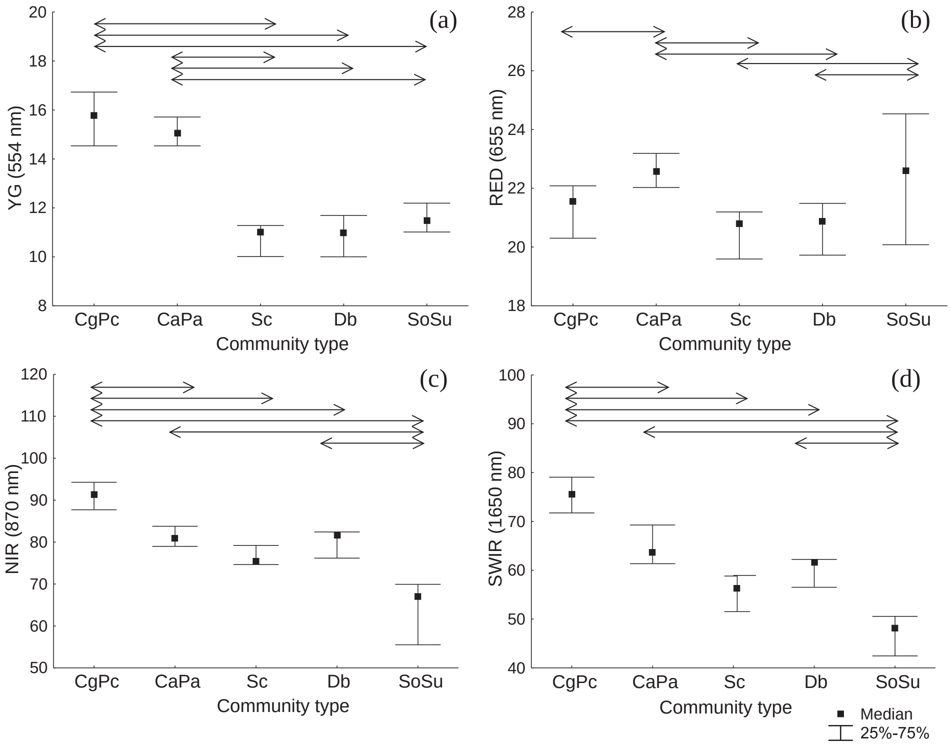

Fig. 3. Differences (*post-hoc* Dunn's test: p<0.05; marked with arrows) in individual spectral band reflenctance: YG (a), RED (b), NIR (c) and SWIR (d) among community types: CgPc – *Cochlearia groenlandica–Prasiola crispa*, CaPa – *Cerastium arcticum–Poa alpina*, Sc – *Saxifraga caespitosa*, Db – *Deschampsia borealis*, SoSu – *Saxifraga oppositifolia–Sanionia uncinata*.

Table 2

Kruskal-Wallis test for differences among community types for individual spectral band reflenctance: YG, RED, NIR, SWIR and NDVI index ($p < 0.001$, $n = 134$)

	YG	RED	NIR	SWIR	NDVI
H	74.42	41.6	108.82	104.52	114.13

Table 3

Spearman's correlation coefficient between the 1st DCA axis based on plant species composition (vegetation data) and radiometric data ($p < 0.05$, $n = 134$).

	1st PCA axis (radiometric data)	YG	RED	NIR	SWIR	NDVI
1st DCA axis (vegetation data)	0.86	-0.70	ns	-0.87	-0.88	-0.78

range of YG, NIR and SWIR radiation and from all of them in NDVI values. These differences were not so clear for RED reflectance; nevertheless it was possible to

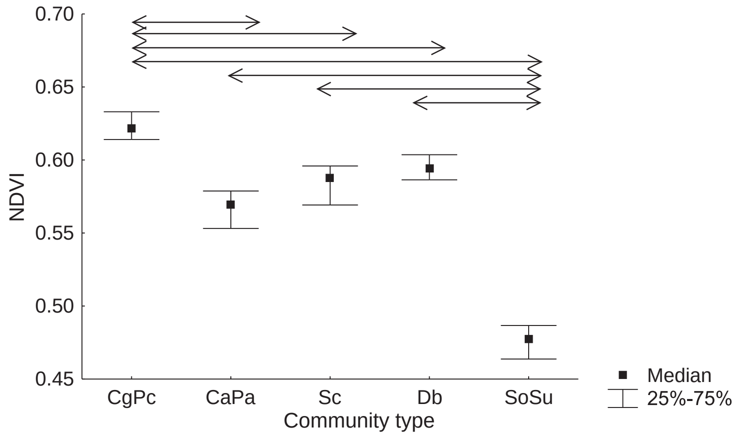

Fig. 4. Differences (*post-hoc* Dunn's test: p <0.05; marked with arrows) in NDVI index among community types: CgPc – *Cochlearia groenlandica–Prasiola crispa*, CaPa – *Cerastium arcticum–Poa alpina*, Sc – *Saxifraga caespitosa*, Db – *Deschampsia borealis*, SoSu – *Saxifraga oppositifolia–Sanionia uncinata*.

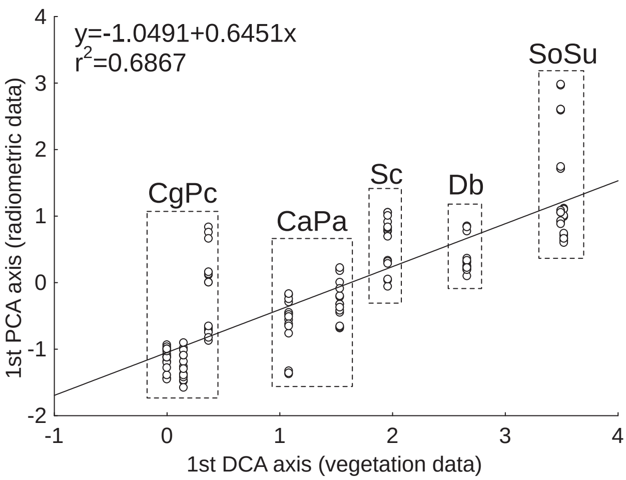

Fig. 5. Relationship (Spearman rank correlation, p<0.001) between 1st DCA axis based on plant species composition (vegetation data) and 1st PCA axis based on individual spectral band reflenctance: YG, RED, NIR and SWIR (radiometric data) and distinct community types marked: CgPc – *Cochlearia groenlandica–Prasiola crispa*, CaPa – *Cerastium arcticum–Poa alpina*, Sc – *Saxifraga caespitosa*, Db – *Deschampsia borealis*, SoSu – *Saxifraga oppositifolia–Sanionia uncinata*.

distinguish CgPc from the next one, *Cerastium arcticum–Poa alpina*, and SaSu from adjacent *Deschampsia borealis* and subsequent *Saxifraga caespitosa* communities. Generally, we found more differences among communities in the range of YG, NIR and SWIR radiation comparing with RED reflection values.

Despite some differences in the results of PCA analysis of radiometric data comparing with DCA based on plant species composition, general ordination of

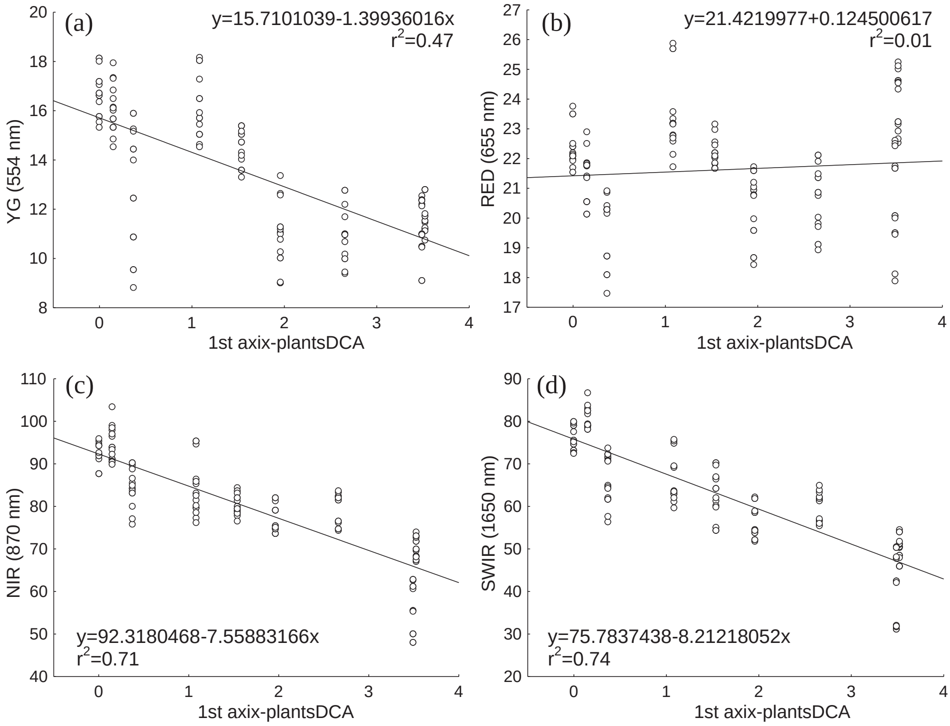

Fig. 6. Relationship (Spearman rank correlation, $p < 0.05$) between 1st DCA axis based on plant species composition (vegetation data) and individual spectral band reflenctance: YG (a), RED – nonsignificant (b), NIR (c) and SWIR (d).

the communities was very similar. We found strong positive correlation ($r_S = 0.86$, $p < 0.001$, $n = 134$) between the sample scores of the 1st DCA axis based on vegetation data and the 1st PCA axis based on individual spectral band reflenctance: YG, RED, NIR and SWIR (Table 3, Fig. 5).

The first PCA axis correlated negatively with all radiometric parameters with the exception of RED reflectance waveband (Table 3, Figs 6, 7). The strongest relationships with spatial vegetation characteristics were observed for NIR and SWIR radiation, the weakest one for YG. Although there were no correlation between the 1st PCA axis and reflection values for red radiation, relationship between this axis and NDVI index (depending on RED and NIR reflection values) was still significant and negative.

Significant correlations were found for radiometric characteristics of vegetation related to its dry biomass. We observed a decrease of NDVI index together with increasing values of total biomass ($r_S = -0.79$, $p < 0.05$, $n = 134$; Fig. 8). After division of total vegetation into vascular plants and mosses, the strength of this relationship weakened for mosses ($r_S = -0.37$, $p < 0.05$, $n = 134$) but almost did not changed for vascular plants ($r_S = -0.78$, $p < 0.05$, $n = 134$).

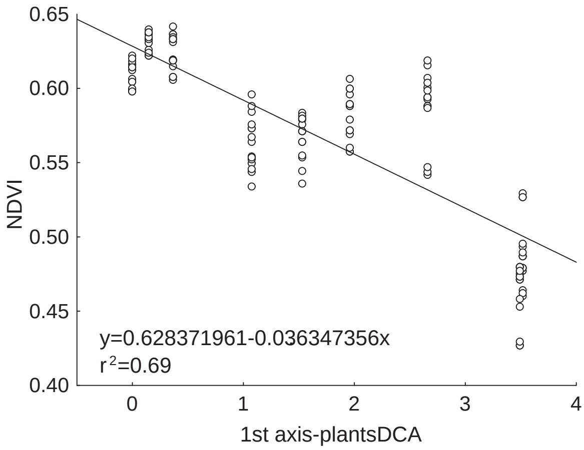

Fig. 7. Relationship (Spearman rank correlation, $p < 0.05$) between 1st DCA axis based on plant species composition (vegetation data) and NDVI index.

Discussion

All plants use only a part of the solar radiation for their photosynthetic processes. The amount of incident radiation depends on latitude, altitude, season, time of a day and habitat. Part of energy is absorbed by plants and the rest is reflected from their surface. Photosynthetically active radiation ranging from 400 to 700 nm (visible light – YG and RED wavebands in our study) is absorbed by photosynthetic pigments. The range of NIR and SWIR (infrared – over 700 nm) is absorbed by water. Thus, in contrast to the visible band, the infrared absorption depends on the thickness of leaves and their water content (Ray 1994; Zarco-Tejada *et al.* 2003; Piekarczyk 2005; Pilarski 2005).

Many factors may influence solar radiation reflectance. Cover of vegetation is recognized as its main attribute determining spectral response (Tucker 1977; Liu *et al.* 2007). Since our nine study plots had very similar plant cover, this parameter could not be responsible for reflectance differentiation and some structural features of community, like species composition, species-dependent shape or surface structure of leaves, decided on signal intensity from particular radiometer channels. It is known that different species have different spectral properties and that radiometric response of each area is the sum of radiation reflection from all individual plants (Strąg and Barcikowski 2002). Hence, various levels of reflectance observed along the transect could respond to the differences in species composition between particular sample plots. Also biotope characteristics, mainly soil surface colouration and structure, but also soil water and different ions content, pH and salinity might be of great importance (Behrens *et al.* 2004; Kooistra *et al.* 2004; Schmidtlein *et al.* 2005; Fernández-Buces *et al.* 2006).

Our results confirm the hypothesis that the use of radiometric data enables classifying particular plant communities (Figs 1, 2 and 5), as was suggested by some authors (Hope *et al.* 1993; Trodd 1996; Strąg and Barcikowski 2002; Thomas *et al.* 2002). The best distinguished communities from the ornithogenic tundra studied were *Cochlearia groenlandica–Prasiola crispa*, situated directly under the seabirds' colony, and *Saxifraga oppositifolia–Sanionia uncinata*, nearby the seashore, both predominated with one or two species. Other communities, i.e. *Cerastium arcticum–Poa alpina*, *Deschampsia borealis* and *Saxifraga caespitosa*, did not have so strong dominance of any taxon and had greater than CgPc and SoSu proportion of other species. Many of them appeared in the plots located in the central part of the transect (within communities CaPa, Sc and Db) causing that spectral properties of these plots could be more similar and samples belonging to these communities sometimes overlapped each other on the diagram.

Differences in radiometric characteristics between community types appeared the weakest for RED radiation (Figs 3, 4, Table 2). It could be explained by uniformly high cover of vegetation and consequently, similar photosynthetic activity of all distinguished communities. Differentiation found in other reflectance wavelengths could be the result of differences in some structural or functional attributes of the vegetation, *e.g.* leaves' thickness, shape, superficial structure and/or position in relation to solar incident radiation, water content in plant tissue and many others. Facing quite similar situation, with no clear differences in RED radiation among studied plots, Piekarczyk (2005) calculated Moisture Stress Index (MSI) which divided SWIR by NIR. In our case combination of RED and NIR reflectance values in NDVI calculation seemed to be the best solution to reveal actual variability among plant communities (Laider and Treitz 2003). Differences in this index among particular communities confirmed precisely the results of ordination of data from four spectral reflectance channels, where communities CgPc and SoSu were separated from the others, which were more similar to each other.

We found significantly negative relationships between plant species composition (DCA ordination results) and particular radiometric data (YG, NIR and SWIR radiation and NDVI index) but it appeared insignificant for RED band, again (Figs 6, 7, Table 3). These results corresponded well with those described previously. Red radiation, as dependent mainly on chlorophyll amount and thus on vegetation cover, did not change much with increasing distance from the colony to the sea, along a gradient expressed by the 1st DCA axis, because the cover of plants did not change there as well, constituting more or less 95% of the ground surface in most of the sample plots. So, significant decrease of remaining light bands and also NDVI index had to be related with other structural or/and functional features of vegetation or/and some biotope properties.

Relationship between spectral properties of vegetation and the amount, defined as biomass, density or cover, of its photosynthesizing tissues was a subject of many studies (Laider and Treitz 2003). The nature of these relations could create some difficulties being sometimes linear, asymptotic or even insignificant. In monospecific areas, the reflectance of RED and NIR regions of the spectrum or

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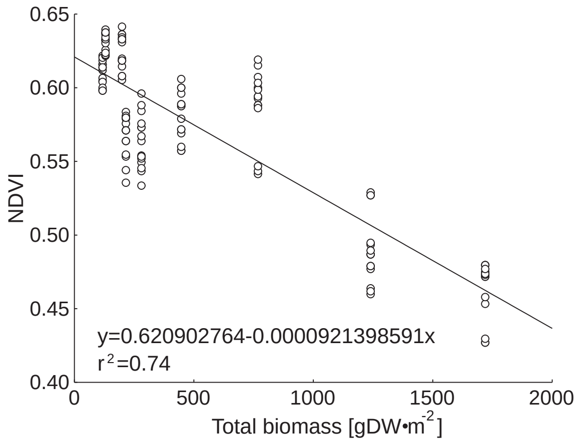

Fig. 8. Relationship (Spearman rank correlation, p <0.05) between NDVI index and total biomass of vegetation.

combinations of these two wavebands was strongly correlated with biomass, leaf area, water and chlorophyll content (Lorenzen and Jensen 1988). We observed significant but negative dependence between NDVI index and dry mass of vegetation (Fig. 8). However, our study plots consisted of several species of vascular plants and mosses in various proportions. Moreover, whereas the radiometer recorded spectral reflectance from live plants, our data used in calculations concerned their dry biomass. This procedure might change the results. Some of the plant species, as *Cochlearia groenlandica* dominating in some plots and being also abundant in others, were characterised by relatively large and well-hydrated leaves. After drying, their proportion in plant biomass of particular sample plots dramatically decreased in comparison with less hydrated plants.

Our results support the statement of many authors that radiometric analysis of vegetation can be a very useful method of studying the structure and functioning of plant formations on various scales (Tucker 1980; Hobbs 1990; Strąg and Barcikowski 2002; Starks *et al.* 2006). However, our study area was situated in a very specific region due to continuous polar day that lasts there about 117 days, although the sun is rather low above the horizon. Moreover, the transect was marked out along a steep slope, so the incident radiation could reach the vegetation at a different angle (Gao *et al.* 2000; Combal and Isaka 2002; Behrens *et al.* 2004). Bearing in mind that Arctic ornithogenic tundra was very specific and spatially limited, and that sampling schemes, radiometer height above ground and its field of view, bandwidth and sensitivity, as well as calibration techniques are rarely standardized across studies (Laidler and Treitz 2003), we have to be cautious in interpretation of the results obtained.

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