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# Spectral characteristics of bryophyte carpet and mat subformation showing a vitality-dependent color pattern: Comparison for two distant regions of maritime Antarctica

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## Abstract

Spectral characteristics of the bryophyte carpet and mat subformation on Nelson Island (South Shetlands Islands) and Galindez Island (Argentine Islands, Graham Coast) were analyzed using spectral reflectance characteristics. A set of 9 specific reflectance indices were calculated and compared between two locations for the same type of moss vegetation formed by *Sanionia georgicouncinata* and *Warnstorfia* spp. The Normalized Difference Vegetation Index (NDVI) is efficient in discriminating between the two contrasting color/ecological moss community classes, *i.e.* such as less vigorous or dead and vigorous. However, NDVI is not sufficiently sensitive to discriminate intermediate vitality states. Presented data also demonstrates that complementary application of two indices, NDVI and Photochemical Reflectance Index (PRI), can be promising for follow-up studies focused on the determination of the color differences attributed to ecolophysiological state of a moss community. With the same values of NDVI, bryophyte carpet and mat subformation on Galindez Island are characterized by higher values of the OSAVI, which can be used as an indicator for further monitoring.

***Key words:*** spectral reflectance, maritime Antarctica, moss communities, ecological monitoring, NDVI, PRI, moss species resistance, Galindez Island, Nelson Island

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## Introduction

The unique Antarctic ecosystems are subjected to increasing anthropogenic impacts and ongoing environmental changes related to local warming and consequent alterations in water availability. In their recent work, Colesie et al. (2023) have described the current state of the Antarctic vegetation and predicted future changes. While they did not predict a universal pattern, the changes of the Antarctic terrestrial environments are expected to be rapid and drastic, but significantly different in maritime and continental Antarctica. Apart from a warmer and drier microclimate, resistance of particular moss species to both these factors could be another driver affecting ecophysiological behavior of mosses in the future. Shortlidge et al. (2017) investigated the impact of six years of *in situ* passive warming on moss communities via open top chambers on King George Island and concluded that passive warming would impact moss physiology, potentially enabling greater resource investment into growth and reproduction. Climate change in Antarctica are predicted to altered water availability. Therefore, desiccation tolerance of different vegetation components of the Antarctic terrestrial ecosystems, including mosses, is a very important parameter. It is well known that mosses can tolerate desiccation due to the establishment of mechanisms that involves the control of the homeostasis redox, the osmotic adjustment and the accumulation of molecules like osmolytes and dehydrins that stabilizes the cell and their components (Pizarro et al. 2019).

Recent studies addressed different aspects of the Antarctic vegetation including dessication and cold tolerance. In our previous studies of photosystem II effectivity and quenching mechanisms in Antarctic lichens we have described and discussed interspecific differences in desiccation tolerance (Puhovkin et al. 2022) and discussed lichen cryoresistance (Hájek et al. 2022, Puhovkin et al. 2023a). Physiological responses to temperature were also investigated in two Antarctic moss species, such as *Ceratodon purpureus* (Hedw.) Brid. and *Schistidium antarctici* (Cardot) L. I. Savicz & Smirnov (Stanton et al. 2013). The results of Wasley et al. (2006) indicate that species studied in their research occupy distinctly different ecological niches with respect to water relations, and provide a physiological explanation for present species distributions.

It is not surprising that the Antarctic vegetation responds to current environmental changes. Thus, vegetation can be used as indicator of these changes. For instance, *Sphagnum* spp. was used as an indicator of climate change in the sub-Antarctica (Whinam and Copson 2006).

Bryophyte carpet and mat subformation (BCMS) represents one of the most abundant vegetation formations of the ice-free areas in maritime Antarctica. This formation is represented on the South Shetlands, in particular on Nelson Island, by communities of *Sanionia georgicouncinata* (Müll.Hal.) Ochyra & Hedenäs. and sometimes by *Warnstorfia sarmentosa* (Wahlenb.) Hedenäs (Lindsay 1971, Ochyra et al 2008, Rosa et al. 2022). On the other hand, on Argentine Islands, BCMS is represented by two variants, with moist habitats dominated by *Warnstorfia fontinaliopsis* and drier habitats by both species of *Sanionia* – *Sanionia georgicouncinata* and *Sanionia uncinata* (Hedw.) Loeske (Smith and Corner 1973, Ochyra et al. 2008, Parnikoza et al. 2018).

Ecophysiological state and vitality of particular species within BCMS is reflected by diffrences in colour pattern. Thus, pattern in colour of moss carpets can be used as a valuable parameter of moss vitality that can be monitor with application of UAV-based or remote sensing techniques. Recently, remote remote assessment of spectral reflectance of vegetation is used for a wide variety of field work ranging from vegetation mapping to classification of vegetation cover and functional properties of vegetation (Rosa et al. 2022). A wide range of vegetation indices have been introduced to monitor vegetation using remote sensing. However, application of the remote sensing techniques for monitoring of vegetation changes in Antarctica is still at infancy.

Recent advances in remote sensing techniques provide opportunity to detect changes in vegetation distribution, and, therefore, could provide a powerful tool for monitoring future vegetation changes. However, due to relatively small areas occupied by vegetation in Antarctica, and its pachy distribution high spatial heterogenity provide significant metodological challenges. Therefore it is difficult to detect species-specific and physiological state-related parameters for the Antarctic mosses and distinguish their peculiarities using a single remote sensing platform. Moreover, the remote sensing analyses requires reliable reference data. Thus, a lack of ground truth hinders remote sensing efforts (Chi et al. 2021).

Spectral reflectance signatures of different components of the Antarctic terrestrial vegetation measured *in situ* by using a high-resolution multispectral image is important for adjustment and interpretation of remote sensing data. Therefore, as demonstrated by Váczi and Barták (2022) field data, obtained typically by UAV or contact measurement, are of great importance. Therefore, spectral pattern of several species of mosses, lichens, and of alga from hyperspectral data obtained recently *in situ* by da Rosa et al. (2022) in Harmony Point, maritime Antarctica are of a great value. However, further studies are needed to provide a database for investigation and monitoring changes in the Antarctic vegetation with application of the remote sensing techniques.

Moreover, it seems to be a rational strategy to combine remote sensing methods with direct acquisition of spectral data using handheld portable spectrometers. In order to establish spectral reflectance-based ecological monitoring of moss cover at long-term experimental sites located on Nelson Island (South Shetland Islands) and Galindez Island (Argentine Islands, Graham Coast), we focused in this work on the following questions: (1) What spectral reflectance indices can be applied to diferentiate between vigorous (green) and less vigorous (brown) mosses? (2) Wether spectral reflectance indices for the same BCMS differ between regions in Antarctic or not? We hypothesized that spectral indices of moss cover (especially NDVI) are related to vitality-dependent colour pattern and can be used to compare moss viability between model sites in different regions in Antarctica.

## Material and Methods

### *1. Experimantal sites*

During the Antarctic summer season of 2022/23 a field survey was conducted at Nelson and Galindez Islands (maritime Antarctica) to identified representative bryophyte carpet and mat subformation patches for the assesment of their spectral reflectance characteristics. In total, seven BCMS sampling sites were selected, with four located on Nelson and three on Galindez Island (Table 1, Figs. 1, 2).

Then, 24 sampling plots, each of 5×5 cm, with stands of relatively homogenous vegetation represented by a single species or single-color pattern were selected and marked with a metal square frame. Ten sampling plots were located on

Nelson Island and included vegetation communities dominated by *Sanionia georgicouncinata*. The remaining 14 sampling plots were located on Galindez Islands and included six plots with *Sanionia georgicouncinata* and six plots with *Warnstorfia fontinaliopsis*. The list of selected sampling plots is given in Table 2 and their color state shown on Fig. 3.

The study sites were chosen in terms of same moss species that would grow simultaneously at two geographically distant locations. In case of Nelson Island BCMS was discontinious stands in lowland places with dranage of melting streams dominated by *S. georgicouncinata* with *W. sarmentosa* and other rarer species. At the same time, the BCMS is represented by monospecific patches, significant inclusion on moss banks at Galindez Island, *see* the studied sites (Table 1).

| **Island** | **Sampling site** | **Site description** | **Coordinates** | **Altitude** |
|---|---|---|---|---|
| Nelson Island, Rip Point | NI 1 | Moss terrace (down)<br>Dominant: *Sanionia georgicouncinata* (Müll. Hal.) Ochyra & Hedenäs; additions: *Bryum pseudotriquetrum* (Hedw.) P.Gaertn., B.Mey. & Scherb. | 62.245267°S, 58.981122°W | 7 m |
| | NI 2 | Moss terrace (up)<br>Dominant: *Sanionia georgicouncinata* (Müll. Hal.) Ochyra & Hedenäs; additions: *Pohlia cruda* (Hedw.) Lindb., *Polytrichastrum alpinum* (Hedw.) G.L.Sm. | 62.243757°S, 58.979941°W | 58 m |
| | NI 3 | Moss terrace (down)<br>Dominant: *Saniona georgicouncinata* (Müll. Hal.) Ochyra & Hedenäs; additions: *Syntrichia filaris* (Müll. Hal.) R.H. Zander, *Bryum pseudotriquetrum* (Hedw.) P.Gaertn., B.Mey. & Scherb., *Polytrichastrum alpinum* (Hedw.) G.L.Sm. | 62.235665°S, 58.998091°W | 20 m |
| | NI 4 | Moss terrace (up)<br>Dominant: *Sanionia georgicouncinata* (Müll. Hal.) Ochyra & Hedenäs with significant presence of *Warnstorfia sarmentosa*; additions: *Pohlia cruda* (Hedw.) Lindb., *Polytrichastrum alpinum* (Hedw.) G.L.Sm., *Brachythecium austroglareosum* (Müll. Hal.) Kindb., *Cephaloziella varians* (Gottsche) Steph. | 62.235708°S, 59.002300W° | 35 m |
| Galindez Island | GI 1 | Moss Valley, Smith moss bank<br>Monodominant inclusions of *Warnstorfia fontinaliopsis* | 65.247620°S, 64.250818°W | 10 m |
| | GI 2 | Govorukha Dome, Eastern terrace, Kupol moss bank<br>Monodominant inclusions of *Sanionia georgicouncinata* and *Warnstorfia fontinaliopsis* | 65.248287°S, 64.245419°W | 35 m |
| | GI 3 | Trykutnyk Ridge,<br>Monodominant inclusions of *Sanionia georgicouncinata* and *Warnstorfia fontinaliopsis* | 65.246294°S, 64.247597°W | 8 m |

**Table 1.** The list of sampling sites for the assessment of vegetation spectral reflectance from Nelson and Galindez Islands, maritime Antarctica.

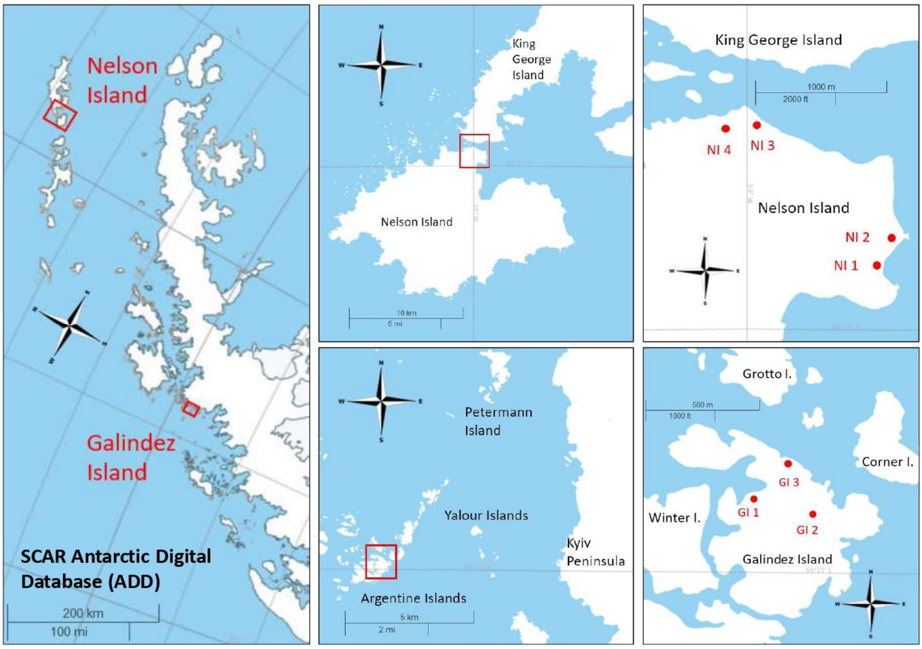

**Fig. 1.** Maps showing the location of sampling sites on Nelson and Galindez Islands, maritime Antarctica. *Map source*: SCAR Antarctic Digital Database (ADD).

| № | Code | Species | Location |
|---|---|---|---|
| 1 | N1 | *Sanionia georgicouncinata* | NI 2 |
| 2 | N2 | *Sanionia georgicouncinata* | NI 4 |
| 3 | N3 | *Sanionia georgicouncinata* | NI 1 |
| 4 | N4 | *Sanionia georgicouncinata* | NI 2 |
| 5 | N5 | *Sanionia georgicouncinata* | NI 4 |
| 6 | N6 | *Sanionia georgicouncinata + Warnstorfia sarmentosa (60:40)* | NI 4 |
| 7 | N7 | *Sanionia georgicouncinata* | NI 4 |
| 8 | N8 | *Sanionia georgicouncinata* | NI 3 |
| 9 | N9 | *Sanionia georgicouncinata* | NI 4 |
| 10 | N10 | *Sanionia georgicouncinata* | NI 3 |
| 11 | 0023 | *Sanionia georgicouncinata* | GI 2 |
| 12 | 0025 | *Sanionia georgicouncinata* | GI 2 |
| 13 | 0055 | *Sanionia georgicouncinata* | GI 2 |
| 14 | 0085 | *Sanionia georgicouncinata* | GI 3 |
| 15 | 0093 | *Sanionia georgicouncinata* | GI 3 |
| 16 | 0088 | *Sanionia georgicouncinata* | GI 3 |
| 17 | 0003 | *Warnstorfia fontinaliopsis* | GI 1 |
| 18 | 0028 | *Warnstorfia fontinaliopsis* | GI 2 |
| 19 | 0002 | *Warnstorfia fontinaliopsis* | GI 1 |
| 20 | 0027 | *Warnstorfia fontinaliopsis* | GI 2 |
| 21 | 0024 | *Warnstorfia fontinaliopsis* | GI 2 |
| 22 | 0054 | *Warnstorfia fontinaliopsis* | GI 2 |
| 23 | 0026 | *Warnstorfia fontinaliopsis* | GI 2 |
| 24 | 0053 | *Warnstorfia fontinaliopsis* | GI 2 |

**Table 2.** The list of species selected for the assesment of spectral reflectance.

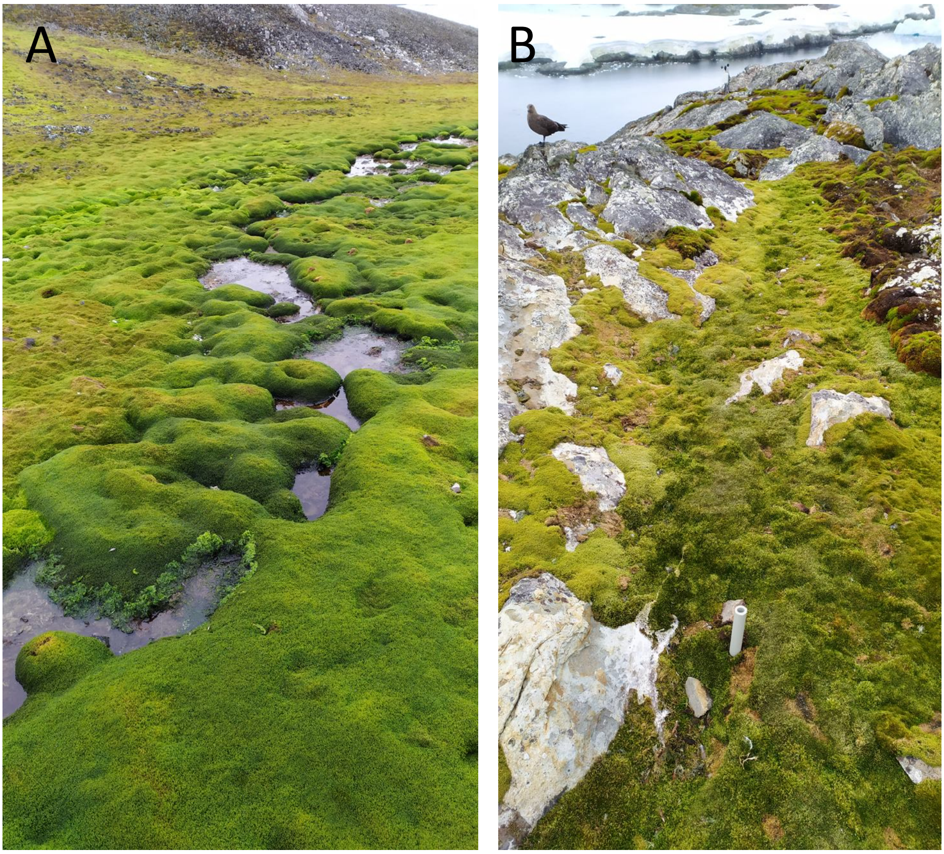

**Fig. 2**. General view of a typical bryophyte carpet and mat subformation on Nelson (A) and Galindez (B) Islands.

In all study sites all bryophytes species were collected. The samples were sorted, packed, dried, and identified under magnification using a binocular magnifying glass and binocular microscope and taxonomic keys (Bednarek-Ochyra et al. 2000, Ochyra et al. 2008). Then, bryophytes samples were deposited and are currently housed in the bryophyte herbarium at the W. Szafer Institute of Botany, Polish Academy of Sciences in Kraków (KRAM).

## *2. Spectral reflectance assessment*

PlantPen NDVI 300 and PlantPen PRI 200 (Photon Systems Instruments, Drásov, Czech Republic) were used to measure Normalized Diffrence Vegetaion Index (NDVI) and Pchochemical Reflectance Index (PRI). Reflectance spectra of the moss species were measured by a PolyPen RP 410 NIR (Photon Systems Instruments, Drásov, Czech Republic) within the range of 640–1050 nm. Using Spectrapen software, the several spectral reflectance indices were calculated (*see* Table 3).

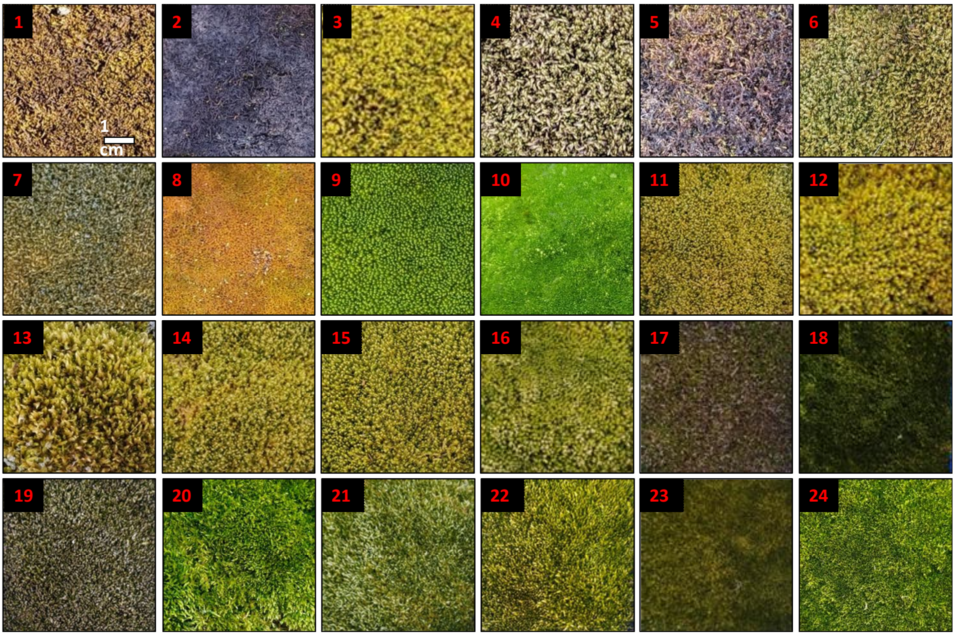

**Fig. 3.** Top view on sampling plots (5 × 5 cm) representing spots of typical bryophyte carpet and mat subformation from Nelson (1–10) and Galindez (11–24) Islands.

| Index | Abbreviation | Equation | Reference |
|---|---|---|---|
| Normalized Difference Vegetation Index | NDVI | NDVI = (RNIR – RRED) / (RNIR + RRED) | Rouse et al. (1974) |
| Simple Ratio Index | SR | SR = RNIR / RRED | Rouse et al. (1974) |
| Zarco-Tejada & Miller Index | ZMI | ZMI = R750 / R710 | Zarco-Tejada et al. (2001) |
| Carter Index | Ctr2 | Ctr2 = R695 / R760 | Carter (1994),<br>Carter et al. (1996) |
| Pigment specific normalized difference a | PSNDa | PSNDa = (R790 – R680) / (R790 + R680) | Blackburn (1998) |
| Gitelson and Merzlyak Index | GM2 | GM2 = R750/ R700 | Gitelson and Merzlyak (1997) |
| Renormalized Difference Vegetation Index | RDVI | RDVI = (R780 – R670)/ ((R780 + R670) ^ 0.5) | Roujean and Breon (1995) |
| Optimized Soil-Adjusted Vegetation Index | OSAVI | OSAVI = (1 + 0.16) × (R790 – R670) / (R790 – R670 + 0.16) | Rondeaux et al. (1996) |
| Photochemical Reflectance Index | PRI | PRI = (R570 – R531) / (R570 + R531) | Gamon et al. (1992) |

**Table 3.** Spectral reflectance indices calculated for the studied bryophyte carpet and mat subformation sites at Nelson and Galindez Islands, maritime Antarctica.

At each 24 sampling plots (Table 2, Fig. 2) ten measurements were done by each instrument (PlantPen NDVI 300, PlantPen PRI 200, Poly Pen RP 410 NIR). All measurements were taken during similar meteorological conditions, *i.e.*: sunny or overcast day, without precipitation.

## Results

Spectral reflectance indices calculated for each sampling plots, including NDVI, PRI, SR, ZMI, Ctr2, PSNDa, GM2, RDVI and OSAVI, are given in Table 4. Data demonstrated that NDVI of BCMS dominant moss subsamples on Nelson Island varied from 0.36 to 0.74. On Galindez Island, for the samples of *Sanionia georgicouncinata*, NDVI varied from 0.46 to 0.57 and from 0.66 to 0.91 in case of *Warnstorfia fontinaliopsis*. These sampling plots generally represented typical colour- and health-variated fragments of the BCMS. Also, they were found casually in the different locations, according to possible visual controlled differences.

In general, the Nelson Island mosses were visually more distinct in terms of colour classes among the investigated sampling plots compared to the Galindez Island sampling plots. At the Galindez Island, *S. georgicouncinata* sampling plots were mostly yellow in colour wheres *W. fontinaliopsis* sampling plots consisted of mosses with bright green colour.

From the relations of the indices to NDVI, it is apparent that they are well correlated, forming linear, logarithmic, or exponential trends (Fig. 4).

The Simple Ratio Index (SR) and NDVI were well corellated. SR values increased exponentially from 2.2 to 20.7 with an increase in NDVI in the range from 0.36 to 0.91. At the same time, for the two distinctly green specimens of *Warnstorfia fontinaliopsis*, SR ranged between 15 and 20, which is more than twice as much as for the other specimens, while the NDVI is only 15% higher. Similar behaviour was also observed for the relation of the ZMI, GM2 to NDVI. The Ctr2 index decreased linearly from 0.65 to 0.07 with the increase in NDVI in the range from 0.36 to 0.91.

It is apparent that comparing the indices for the Nelson Island and Galindez Island sampling plots, for comparable NDVI values, mosses from Galindez are characterized by a significantly higher RDVI value. Similar relationships were also found for OSAVI and NDVI (Fig. 4).

| **Index** | **#1** | **#2** | **#3** | **#4** | **#5** | **#6** |
|---|---|---|---|---|---|---|
| NDVI | 0.364±0.054$^{a}$ | 0.369±0.040$^{a}$ | 0.418±0.068$^{b}$ | 0.457±0.081$^{bc}$ | 0.490±0.061$^{cd}$ | 0.516±0.081$^{d}$ |
| SR | 2.166±0.256$^{a}$ | 2.183±0.210$^{a}$ | 2.479±0.388$^{ab}$ | 2.750±0.506$^{ab}$ | 2.961±0.401$^{abc}$ | 3.244±0.747$^{bc}$ |
| OSAVI | 0.131±0.059$^{a}$ | 0.115±0.025$^{a}$ | 0.158±0.097$^{ab}$ | 0.321±0.156$^{de}$ | 0.219±0.069$^{bc}$ | 0.283±0.102$^{cd}$ |
| ZMI | 1.263±0.056$^{a}$ | 1.289±0.036$^{ab}$ | 1.430±0.113$^{de}$ | 1.483±0.100$^{ef}$ | 1.357±0.058$^{a-d}$ | 1.408±0.108$^{cde}$ |
| Ctr2 | 0.589±0.069$^{l}$ | 0.652±0.031$^{m}$ | 0.460±0.072$^{ij}$ | 0.418±0.076$^{fgh}$ | 0.529±0.061$^{k}$ | 0.389±0.071$^{f}$ |
| PSNDa | 0.409±0.077$^{b}$ | 0.341±0.033$^{a}$ | 0.497±0.105$^{c}$ | 0.569±0.103$^{d}$ | 0.518±0.078$^{c}$ | 0.642±0.085$^{fg}$ |
| GM2 | 1.480±0.117$^{ab}$ | 1.395±0.057$^{a}$ | 1.858±0.202$^{cde}$ | 1.960±0.240$^{def}$ | 1.587±0.111$^{abc}$ | 1.977±0.294$^{def}$ |
| RDVI | 0.101±0.037$^{a}$ | 0.089±0.015$^{a}$ | 0.123±0.061$^{ab}$ | 0.231±0.107$^{de}$ | 0.158±0.042$^{bc}$ | 0.201±0.064$^{cd}$ |
| PRI | 0.082±0.046$^{kl}$ | 0.010±0.009$^{m}$ | 0.137±0.050$^{f}$ | 0.140±0.018$^{ef}$ | 0.071±0.022$^{kl}$ | 0.134±0.025$^{fg}$ |
| **Index** | **#7** | **#8** | **#9** | **#10** | **#11** | **#12** |
| NDVI | 0.616±0.091$^{f}$ | 0.624±0.052$^{f}$ | 0.724±0.036$^{gh}$ | 0.743±0.058$^{gh}$ | 0.460±0.020$^{c}$ | 0.463±0.018$^{c}$ |
| SR | 4.462±1.203$^{ef}$ | 4.403±0.715$^{def}$ | 6.342±0.920$^{gh}$ | 7.097±1.654$^{hi}$ | 2.706±0.144$^{ab}$ | 2.731±0.125$^{ab}$ |
| OSAVI | 0.299±0.130$^{d}$ | 0.337±0.121$^{de}$ | 0.499±0.130$^{fg}$ | 0.466±0.159$^{f}$ | 0.500±0.031$^{fg}$ | 0.473±0.028$^{f}$ |
| ZMI | 1.685±0.187$^{h}$ | 1.414±0.045$^{cde}$ | 1.881±0.139$^{i}$ | 2.003±0.187$^{j}$ | 1.387±0.051$^{b-e}$ | 1.319±0.026$^{abc}$ |
| Ctr2 | 0.313±0.073$^{e}$ | 0.349±0.032$^{e}$ | 0.213±0.022$^{bc}$ | 0.183±0.035$^{b}$ | 0.429±0.026$^{ghi}$ | 0.444±0.015$^{hi}$ |
| PSNDa | 0.695±0.095$^{hi}$ | 0.743±0.046$^{ij}$ | 0.806±0.029$^{kl}$ | 0.824±0.045$^{l}$ | 0.613±0.022$^{def}$ | 0.625±0.013$^{ef}$ |
| GM2 | 2.457±0.437$^{h}$ | 2.038±0.133$^{efg}$ | 3.191±0.321$^{ij}$ | 3.789±0.557$^{k}$ | 1.836±0.101$^{cde}$ | 1.744±0.047$^{bcd}$ |
| RDVI | 0.216±0.082$^{d}$ | 0.242±0.076$^{de}$ | 0.356±0.093$^{fg}$ | 0.336±0.121$^{f}$ | 0.400±0.037$^{ghi}$ | 0.355±0.029$^{fg}$ |
| PRI | 0.139±0.017$^{ef}$ | 0.270±0.029$^{a}$ | 0.103±0.021$^{ij}$ | 0.065±0.016$^{l}$ | 0.197±0.012$^{bc}$ | 0.157±0.013$^{e}$ |
| **Index** | **#13** | **#14** | **#15** | **#16** | **#17** | **#18** |
| NDVI | 0.479±0.022$^{cd}$ | 0.499±0.034$^{cd}$ | 0.563±0.042$^{e}$ | 0.568±0.027$^{e}$ | 0.656±0.025$^{f}$ | 0.651±0.040$^{f}$ |
| SR | 2.845±0.160$^{abc}$ | 3.012±0.264$^{abc}$ | 3.612±0.454$^{cd}$ | 3.648±0.292$^{cde}$ | 4.846±0.459$^{f}$ | 4.794±0.677$^{f}$ |
| OSAVI | 0.383±0.041$^{e}$ | 0.547±0.041$^{ghi}$ | 0.571±0.034$^{hij}$ | 0.531±0.029$^{fgh}$ | 0.512±0.017$^{fgh}$ | 0.636±0.020$^{jk}$ |
| ZMI | 1.275±0.025$^{a}$ | 1.340±0.045$^{a-d}$ | 1.629±0.104$^{gh}$ | 1.538±0.059$^{fg}$ | 1.599±0.065$^{gh}$ | 1.952±0.130$^{ij}$ |
| Ctr2 | 0.493±0.030$^{jk}$ | 0.400±0.035$^{fg}$ | 0.329±0.033$^{e}$ | 0.339±0.023$^{e}$ | 0.323±0.030$^{e}$ | 0.255±0.032$^{d}$ |
| PSNDa | 0.589±0.035$^{de}$ | 0.677±0.031$^{gh}$ | 0.710±0.032$^{hi}$ | 0.694±0.028$^{h}$ | 0.719±0.030$^{hij}$ | 0.763±0.025$^{jk}$ |
| GM2 | 1.602±0.061$^{abc}$ | 1.863±0.115$^{cde}$ | 2.315±0.209$^{gh}$ | 2.216±0.122$^{fgh}$ | 2.280±0.180$^{gh}$ | 2.962±0.312$^{i}$ |
| RDVI | 0.269±0.032$^{e}$ | 0.435±0.042$^{hij}$ | 0.446±0.036$^{ij}$ | 0.396±0.028$^{gh}$ | 0.363±0.012$^{fg}$ | 0.507±0.031$^{kl}$ |
| PRI | 0.137±0.013$^{f}$ | 0.206±0.011$^{b}$ | 0.178±0.008$^{cd}$ | 0.109±0.013$^{i}$ | 0.132±0.012$^{fgh}$ | 0.089±0.017$^{jk}$ |
| **Index** | **#19** | **#20** | **#21** | **#22** | **#23** | **#24** |
| NDVI | 0.710±0.033$^{g}$ | 0.717±0.042$^{g}$ | 0.725±0.049$^{gh}$ | 0.767±0.040$^{h}$ | 0.881±0.006$^{i}$ | 0.907±0.013$^{i}$ |
| SR | 5.989±0.805$^{g}$ | 6.207±1.075$^{g}$ | 6.489±1.460$^{gh}$ | 7.807±1.547$^{i}$ | 15.90±0.92$^{j}$ | 20.74±2.66$^{k}$ |
| OSAVI | 0.610±0.023$^{ijk}$ | 0.613±0.042$^{ijk}$ | 0.675±0.025$^{k}$ | 0.563±0.082$^{ghi}$ | 0.780±0.008$^{l}$ | 0.780±0.013$^{l}$ |
| ZMI | 2.133±0.121$^{k}$ | 1.954±0.114$^{ij}$ | 1.902±0.139$^{ij}$ | 2.318±0.206$^{l}$ | 3.155±0.065$^{m}$ | 4.029±0.322$^{n}$ |
| Ctr2 | 0.224±0.023$^{cd}$ | 0.207±0.026$^{bc}$ | 0.205±0.034$^{bc}$ | 0.187±0.037$^{bc}$ | 0.095±0.003$^{a}$ | 0.072±0.008$^{a}$ |
| PSNDa | 0.763±0.025$^{jk}$ | 0.833±0.026$^{l}$ | 0.826±0.044$^{l}$ | 0.817±0.042$^{l}$ | 0.914±0.004$^{m}$ | 0.932±0.006$^{m}$ |
| GM2 | 3.337±0.294$^{j}$ | 3.302±0.332$^{j}$ | 3.286±0.455$^{j}$ | 3.930±0.582$^{k}$ | 6.513±0.170$^{l}$ | 8.689±0.813$^{m}$ |
| RDVI | 0.458±0.022$^{jk}$ | 0.446±0.037$^{ij}$ | 0.522±0.025$^{l}$ | 0.400±0.066$^{ghi}$ | 0.613±0.011$^{m}$ | 0.602±0.018$^{m}$ |
| PRI | 0.107±0.009$^{ij}$ | 0.114±0.014$^{hi}$ | 0.177±0.018$^{d}$ | 0.105±0.013$^{ij}$ | 0.117±0.017$^{ghi}$ | 0.089±0.025$^{jk}$ |

**Table 4.** Spectral reflectance indices calculated for sampling plots of bryophyte carpet and mat subformation dominated by *Sanionia georgicouncinata* and *Warnstorfia fontinaliopsis* on Nelson and Galindez Island. For images and description of the sampling plots *see* Fig. 2.

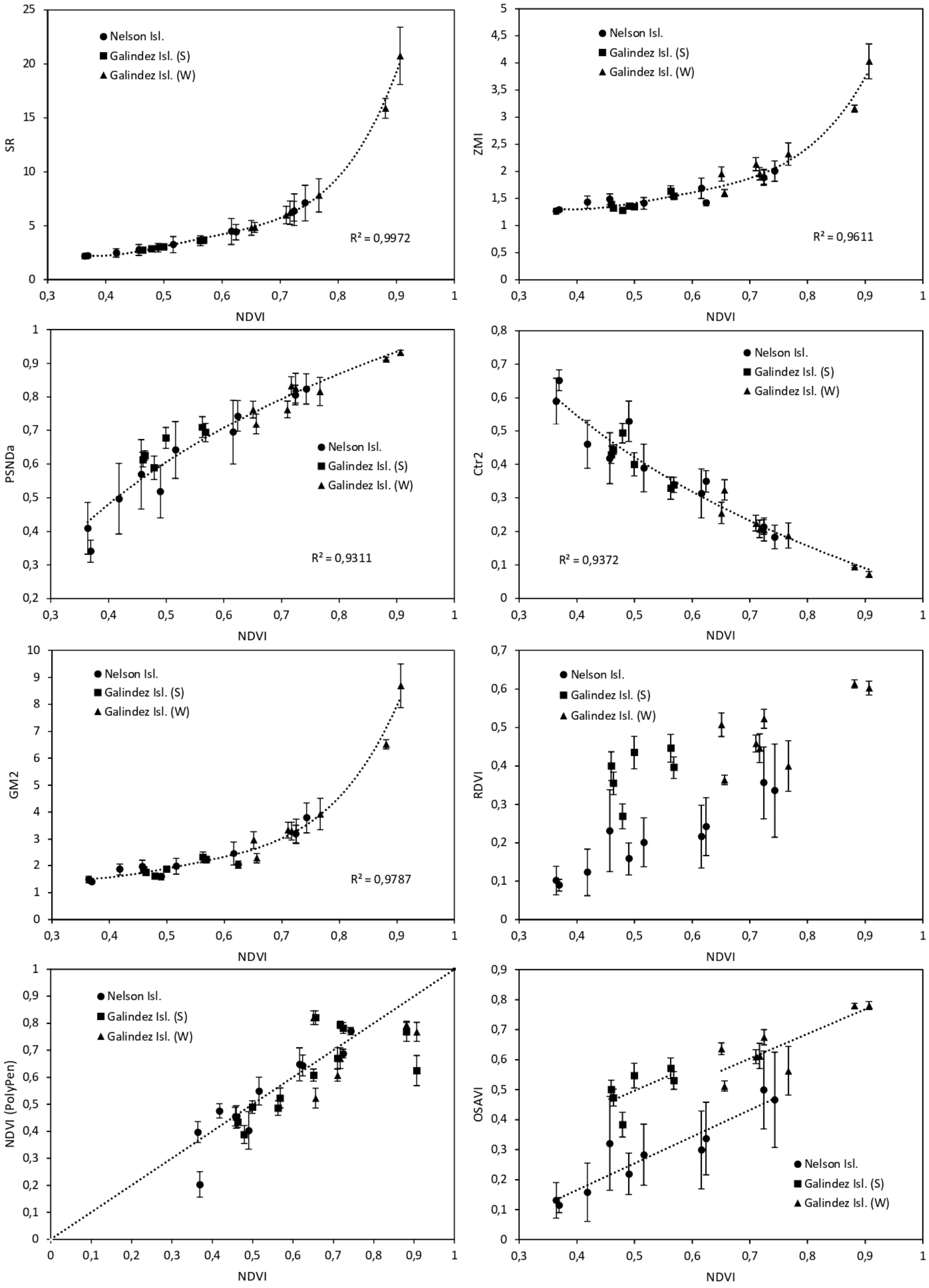

**Fig. 4.** Plots showing relationships between different spectral reflectance indices and NDVI. *Note*: S – *Sanionia georgicouncinata*, W – *Warnstorfia fontinaliopsis*.

## Discussion

NDVI is a widely used index for evaluation of vegetation classification. A higher value of this index is typically associated with a more viable vegetation. Since 2010, when the first remote sensing-based vegetation map in Antarctica was created and NDVI was applied in order to provide a description of the terrestrial vegetation extent on the Antarctic Peninsula, NDVI has been used with an increasing frequency in Antarctica (Fretwell et al. 2011, Jawak et al. 2019). Casanovas et al. (2015) showed an approach capable of the detection of lichen flora on the Antarctic Peninsula, suggesting the use of NDVI for other purposes than vegetation mapping.

According to Sotille et al. (2020) NDVI shows very specific values for different types of the Antarctic vegetation, therefore, this index has very high potential for application in surveys of vegetation in this region. Sotille et al. (2020) also tried to distinguish between different types of vegetation according to NDVI values and concluded that pattern found in NDVI classes is consistent with the spectral behavior of the plant communities of the region and may be used to indicate a certain type of vegetation. On the other hand, Malenovský et al. (2015) investigated applicability of near-infrared spectroscopy for the assessment of spatial differences in viability of a moss bed. This study applied the modified triangular vegetation index 2 (MTVI2) to detect photosynthetically active mosses based on hyperspectral images of study sites.

Moreover, in our previous study (Puhovkin et al. 2023b), we suggested application of NDVI classes (0.1 wide) to detect interseasonal variations in the condition of moss banks. Our four years monitoring has demonstrated that NDVI can be used as a good indicator of ecophysiological state of mosses (Puhovkin et al. 2023b). Present data show that this index is also suitable for determining the functional state of the moss community, varying from 0.35 for brown (less vigorous state) to 0.9 for green (vigorous) mosses (Table 4).

The Figure 5 illustrates spectral reflectance curves for different patterns of BCMS. For instance, in case of *W. fontinaliopsis* and *S. georgicouncinata* variants of BCMS from Galindez Island, the difference between vigorous (green) and less vigorous states is clear visible between 700 and 900 nm. Spectral curves for vigorous moss thalli are characterized by a wide plateau in 750 – 900 nm range while less vigorous fragments of BCMS (with a typical colour change from vigorously green to yelow and brown) reach maximum values within the range of 900 – 1000 nm. For both regions compared in our study, the spectral response for these groups is similar. Therefore, it is possible to create a single recognition system for them aimed at comparative monitoring.

We used two devices to determine NDVI values, *i.e.*: PlantPen and Polypen. Data demonstrates a high corelation between data obtained by both instuments, despite limited set of measurements (*see* Fig. 4). At the same time, the NDVI is not reliable to determine the specific state of the bryophytes community and discriminate between different intermediate states. Visually brown and yellow and greenish yellow showed very close values for different color patterns within 0.45-0.6 NDVI range. Therefore, it is important to select an index or indices that would discriminate sufficiently between different vitality and colour patterns of the moss community and could be applied as indicators for further monitoring.

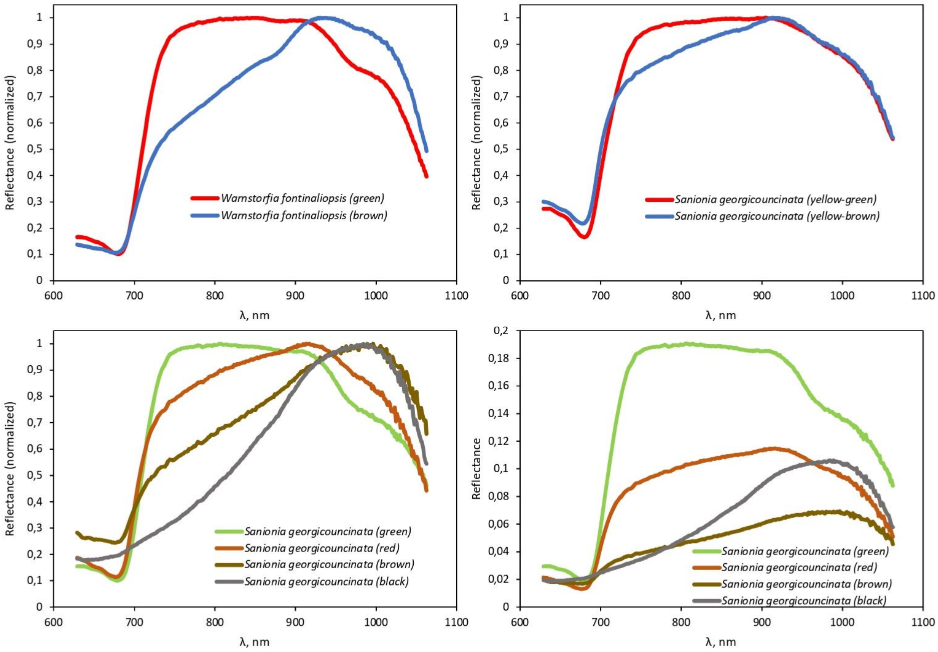

**Fig. 5.** Spectral reflectance curves for different fragments of bryophyte carpet and mat subformation on Nelson and Galindez Islands. *Legend*: A – *Warnstorfia fontinaliopsis*, Galindez Island, normalized spectra; B – *Sanionia georgicouncinata* dominated bryophyte carpet and mat formation, Galindez Island, normalized spectra; C – *S. georgicouncinata* dominated bryophyte carpet and mat formation, Nelson Island, normalized spectra; D – *S. georgicouncinata* dominated bryophyte carpet and mat formation, Nelson Island.

The values of the OSAVI measured at the sampling plots on Galindez Island (both for *Sanionia* and *Warnstorfia*) age generally higher compared to the sampling plots on Nelson Island despite similar values of NDVI (Fig. 4). A similar relationship is also observed for the RDVI. However, the main advantage of OSAVI over RDVI is its simplified formulation and the absence of a requirement for *a priori* knowledge of the soil type. The residual variation of OSAVI due to soil is also evenly distributed over the entire range (0-1) of vegetation cover (Steven 1998). The author also discussed the impact of environmental parameters on OSAVI and concluded that the index has low sensitivity to them. Moreover, Fern et al. (2018) demonstrated that OSAVI is the most reliable estimator of green biomass and vegetation cover in semi-arid regions.

Thus, higher values of the OSAVI, despite similar NDVI values, are associated with better vegetation viability. Therefore, this index can be recommended for parallel monitoring of moss cover applied together with NDVI.

Among the indices investigated in our current study, PRI did not correlate with the NDVI, which apparently indicates different aspects of plant physiological state than reflect by NDVI (Fig. 4). While PRI is associated with carotenoid content in sample, NDVI is used as a proxy of chlorophyll and water contents. Thus, PRI defined as a normalized difference index using two narrow reflectance bands at 531 and 570 nm is closely related to xanthophyll cycle pigment content (Gamon et al. 1992).

Similarly, Lovelock and Robinson (2002) demonstrated that concentration of total chlorophyll was only weakly correlated with several other indices. However, the strongest linear regression was found between total chlorophyll and reflectance indices calculated with reflectance measured at 850 and 680 nm (*i.e.* NDVI). Our data showed that BCMS fragments with similar NDVI values, but higher PRI values are visually red, that is less viable due to exposure to stress factors. Therefore, simultaneus applications of both spectral indices, *i.e.* NDVI and PRI, appers useful for determination of the state of vegetation communities.

Although Lovelock and Robinson (2002) reported that differences in reflectance characteristics across sites and species were not clearly linked to changes in pigment concentrations, they concluded that the PRI was the surface reflectance index was the most sensitive in relation to variation in pigment compositions and photosynthetic function. PRI appears to be sensitive to the relative water content (RWC), typically at the RWC below 20%. This seems to limit applicability of PRI in evaluation of pigment content. However, majority of spectral reflectance measurements were done in well hydrated samples minimizing the effect of dehydration on PRI. For more data, *see* apparent from the species-specific curves presented by Trnková and Barták (2017), and Orekhova et al. (2022).

Based on our data, three categories of mosses can be recognized (Fig. 6) using the PRI *vs.* NDVI plot. They are marked as A, B and C respectively.

The category A includes visually dark mosses, typically brown or grey in color, either dead or exhibiting low vitality due to exposure to some environmental stress. This category is characterized by low both NDVI and PRI values ranging between 0.2-0.5 and 0-0.1, respectively. The category B consists of visually yellow (or reddish) mosses that are rather a at normal viable state, possibly with a slight environmental stress, for instance due to lack of water or due to excessive bird impacts (*e.g.* excessive manuring from penguin colonies). This group includes mosses with moderate NDVI values, ranging between 0.4-0.62, and high PRI values between 0.13-0.27. Finally, the category C consists of visually bright green and vigorous mosses characterized by high NDVI ranging between 0.58-0.9 and moderate PRI values ranging between 0.06-0.18.

Thus, after clustering the data into categories (Fig. 6) it is possible to draw boundaries between these groups. Of course, the accuracy of these boundaries is subject to further refinement. It is necessary to include larger number of fragments studied, as well as other attributes related to plant growth conditions to the consideration.

Considering the typical color patterns of the *S. georgicouncinata* variant of BCMS, it appears that habitats on Nelson Island probably provide more favorable conditions for their development compared to Galindez Island ranging from dry (the least vigorous *S. georgicouncinata*) to very humid (*W. sarmentosa* complement). For instance, bryophyte carpet and mat subformation of *Sanionia georgicouncinata* on Galindez Island are often exposed to repetitive drying/wetting cycles resulting in their lower vitality and yellowish color. In contrast, it appears that such conditions do not impact development of *W. fontinaliopsis* carpets, which is reflected in their typically bright green color. More detailed investigations of habitat variability and environmental requirements for development and existence of both species is needed (particularly water availability and temperature variation) to understand their spectral responses and monitoring of their responses to environmental changes.

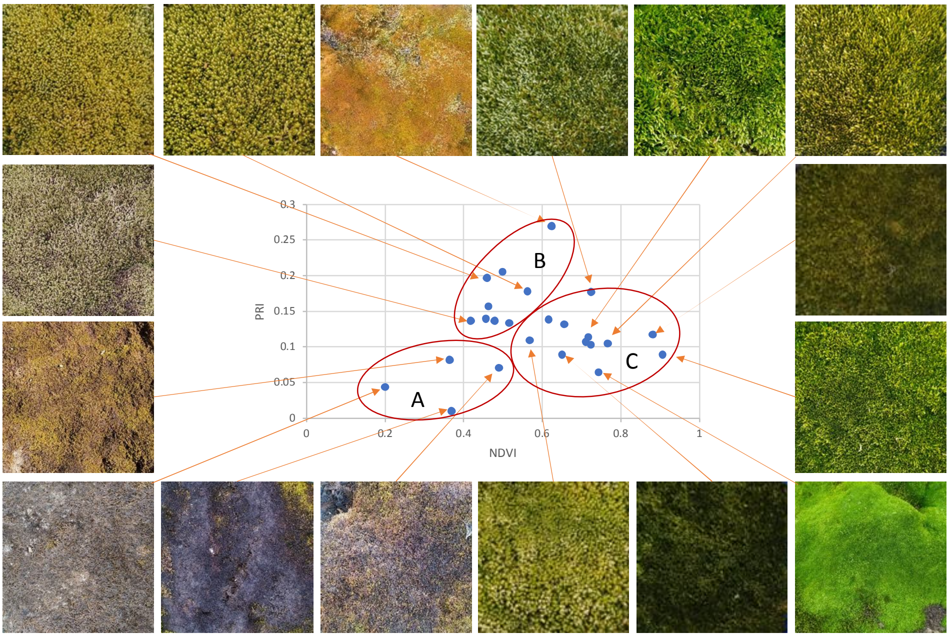

**Fig. 6.** PRI versus NDVI plot showing data for the moss sampling plots representing typical bryophyte carpet and mat subformation for Nelson and Galindez Islands. *Note*: Pictures surrounding the plot demonstrate 16 representative sampling plots, the remaining plots consisted of mosses that were very similar in color.

## Conclusions

1. The NDVI discriminates well between brown and green states of the Antarctic bryophyte carpet and mat subformation but it is not efficient to discriminates intermediate states.
2. Complementary application of PRI, appears to be promising for follow-up studies focused on the determination of the color differences attributed to ecolophysiological state of a moss community.
3. Complementary application of OSAVI, can be used as an indicator for monitoring of bryophyte carpet and mat subformation in Antarctica.

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