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Do spectral reflectance indices distinguish between the greenness in three different moss species in moss banks on Galindez Island (Argentine Islands)?

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Abstract
Spectral reflectance indices of green state of *Warnstorfia fontinaliopsis, Chorisodontium aciphyllum* and *Sanionia georgicouncinata* on moss bank in the Galindez Island (Argentine Islands) were measured using a handheld spectrometer PolyPen RP 410 UVIS (Photon Systems Instruments, Drásov, Czech Republic) within the range of 380–790 nm in order to find suitable ones for effective classification of moss species within the same colour state (green). Among altogether 19 indices tested, there were some which did not differ significantly between the studied species (subgroup 1). Other indices (subgroup 2) were sensitive enough to distinguish one of the studied species from the others, and finally (subgroup 3), they were found statistically significantly different for all studied moss species. Also, the indices calculated at wavelengths typical for UAV spectral cameras (green, red and red edge channels) showed species-specific differences and can be potentially used to distinguish between different mosses within the same green physiological state indicating a good vigor.

Key words: spectral reflectance, maritime Antarctica, *Warnstorfia fontinaliopsis, Chorisodontium aciphyllum*, *Sanionia georgicouncinata*, ecological monitoring, NDVI, moss species resistance

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Introduction

Antarctic terrestrial ecosystems face some of the most extreme growth conditions (Robinson et al. 2003). Therefore, vegetation is changing rapidly in response to a drying climate in East Antarctica (Robinson et al. 2018). Combination of isolation, strong gradients, and marked spatial heterogeneity makes ecological research in Antarctica very important (Convey et al. 2014). Plants like mosses can be sensitive stress markers of environmental influences, including climate change (Malenovský et al. 2017).

Remote sensing using unmanned aerial vehicle (UAV) is increasingly being used to monitor the characteristics of vegetation in polar regions in order to detect climate change impacts (Royles and Griffiths 2015, Zmarz et al. 2023). UAV spectral data are typically used for the evaluation of vegetation classes in polar regions (*e.g.* Calviño-Cancela and Martín-Herrero 2016). First regional map of vegetation of anywhere on the Antarctic continent based on remote sensing data was created by Fretwell et al. (2011); the first study to acquire low altitude aerial photography over Antarctic moss beds with a multi-rotor UAV performed by Lucieer et al. (2014). Malenovský et al. (2015) assessed Antarctic moss stress based on chlorophyll content and leaf density retrieved from imaging spectroscopy data.

Investigation of Antarctic moss health using UAV imagery was presented by Turner et al. (2014, 2018). The ultra-high-resolution image mosaic and digital elevation model provided by the UAV surveys allowed differential detection of changes in vegetation during two distinct periods (Miranda et al. 2020). Sandino et al. (2023) used spectral data to classified some common mosses and lichens.

Flight protocols and processing of spectral image data are very diverse and are usually related to the available aircraft type and the size of the monitoring areas. Our area of interest is the monitoring of moss banks state dynamics, primarily in the area of the Ukrainian Antarctic station Vernadsky. In our previous studies and the study reported in this paper as well, we used a drone.

In this region, such moss banks are usually small in area, or their individual distinct parts do not exceed several thousand square meters. Dominant moss is *Polytrichum strictum* Brid. but the presence of other species can also be significant, namely *Chorisodontium aciphyllum* (Hook.f. & Wilson) Broth., *Warnstorfia fontinaliopsis* (Müll. Hal.) Ochyra and *Sanionia georgicouncinata* (Müll. Hal.) Ochyra & Hedenäs (Wierzgoń et al. 2023). *Chorisodontium aciphyllum* is the second main species in tall moss turf subformation but not so abundant in Argentine Islands – Kyiv Peninsula region. In addition, *Sanionia georgicouncinata* and *Warnstorfia fontinaliopsis* are the main elements of the most widespread vegetation community in the Antarctica – bryophyte carpet and mat subformation (Ochyra et al. 2008).

One of the monitoring parameters we use is the distribution of colour states of moss cover (usually green and brown). Also, spectral characteristics of bryophyte carpet and mat subformation showed a vitality-dependent color pattern (Puhovkin et al. 2023). For describing the condition of a moss bank, particularly its vitality, an integral parameter of the area covered by moss cover of a particular state may be quite suitable. However, given the diversity of mosses, we wondered whether it was possible to distinguish between different species within the same colour state (green) using spectral reflectance indices. Therefore, the approach of a low flying height of dron (UAV) equipped with 4-band multispectral camera was used.

The aim of this study was to determine the spectral reflectance indices of green state of different moss species on moss bank using a handheld spectrometer in order to find suitable ones for moss species classification based on spectral signatures.

Material and Methods

The study was performed in the summer season of 2023/24 during the XXVIII Ukrainian Antarctic expedition. The measurements were carried out on the moss bank Kupol (-65.2481, -64.2462), which is No23 according to Wierzgoń et al. (2023) on Galindez Island under the same conditions (parallel measurement).

Given the relatively small area of the object under study, we use a standard drone flight altitude of 25 m, which ensures high resolution of the spectral images. In this way, it has the potential to distinguish between small spots (approximately 10 * 10 cm), as they account for a sufficient number of pixels. A handheld spectrometer typically provides a continuous spectrum, while drone spectral cameras are based on the use of several defined multispectral camera channels.

Reflectance spectra of mosses *Warnstorfia fontinaliopsis, Chorisodontium aciphyllum* and *Sanionia georgicouncinata* were measured by a PolyPen RP 410 UVIS (Photon Systems Instruments, Drásov, Czech Republic) within the range of 380–790 nm.

On the surface of the moss bank, 5 uniform green state fragments 10 x 10 cm in size were selected for each species studied, where they were presented homogeneously without interspersed with others. Using a spectrometer PolyPen, 5-10 measurements of reflectance spectra were taken for each fragment. Using Spectrapen software, the following spectral reflectance indices were calculated (*see* Table 1).

Species-specific differences in particular spectral reflectance indices were analyzed by one-way ANOVA using Origin Pro (OriginLab Corporation, USA). Statistically-significant differences were considered at $P = 0.01$.

Results

The reflection spectra are shown in Fig. 1 and represent the average values for all measurements (25-40 replicates) for each moss species, respectively. Despite the rather similar shape of the spectra of the three moss species under study, some differences can still be noted. In the case of *Warnstorfia fontinaliopsis*, a relatively smaller peak is observed in the wavelength range of 500-680 nm. In addition, the difference between the spectral curves is in the wavelength range above 720 nm.

Based on the spectra, the following spectral reflectance indices were calculated using standard Spectrapen software (PSI, Czech Republic) (Table 2).

Index	Abbre-viation	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)
Modified Chlorophyll Absorption in Reflectance Indices	MCARI MCARI1	MCARI = [(R700 – R670) – 0.2 * (R700 – R550)] * (R700/ R670) MCARI1 = 1.2 * [2.5 * (R790 – R670) – 1.3 * (R790 – R550)]	Daughtry et al. (2000); Haboudane et al. (2004)
Transformed CAR Index	TCARI	TCARI = 3 * [(R700 – R670) – 0.2 * (R700 – R550) * (R700 / R670)]	Haboudane et al. (2002)
Triangular Vegetation Index	TVI	TVI = 0.5 * [120 * (R750 – R550) – 200 * (R670- R550)]	Haboudane et al. (2004)
Greenness Index	G	G = R554 / R677	Zarco-Tejada et al. (2005)
Zarco-Tejada & Miller Index	ZMI	ZMI = R750 / R710	Zarco-Tejada et al. (2001)
Simple Ratio Pigment Index	SRPI	SRPI = R430 / R680	Peñuelas et al. (1995a)
Normalized Phaeophytinization Index	NPQI	NPQI = (R415 – R435) / (R415+ R435)	Peñuelas et al. (1995b)
Normalized Pigment Chlorophyll Index	NPCI	NPCI = (R680 – R430) / (R680+ R430)	Peñuelas et al. (1994)
Carter Indices	Ctr1 Ctr2	Ctr1 = R695 / R420 Ctr2 = R695 / R760	Carter (1994), Carter et al. (1996)
Pigment specific normalized difference a	PSNDa	PSNDa = (R790 – R680) / (R790 + R680)	Blackburn (1998)
Structure Insensitive Pigment Index	SIPI	SIPI = (R790 – R450) / (R790 – R650)	Peñuelas et al. (1995a)
Gitelson and Merzlyak Indices	GM1 GM2	GM1 = R750/ R550 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)
Anthocyanin Reflectance Indices	ARI1 ARI2	ARI1 = 1/R550 – 1/R700; ARI2 = R790*(1/R550 – 1/R700)	Gitelson et al. (2001)
Carotenoid Reflectance Indices	CRI1 CRI2	CRI1 = 1/R510 – 1/R550; CRI2 = 1/R510 – 1/R700	Gitelson et al. (2002)

Table 1. Desctiption of the spectral reflectance indices calculated in the study.

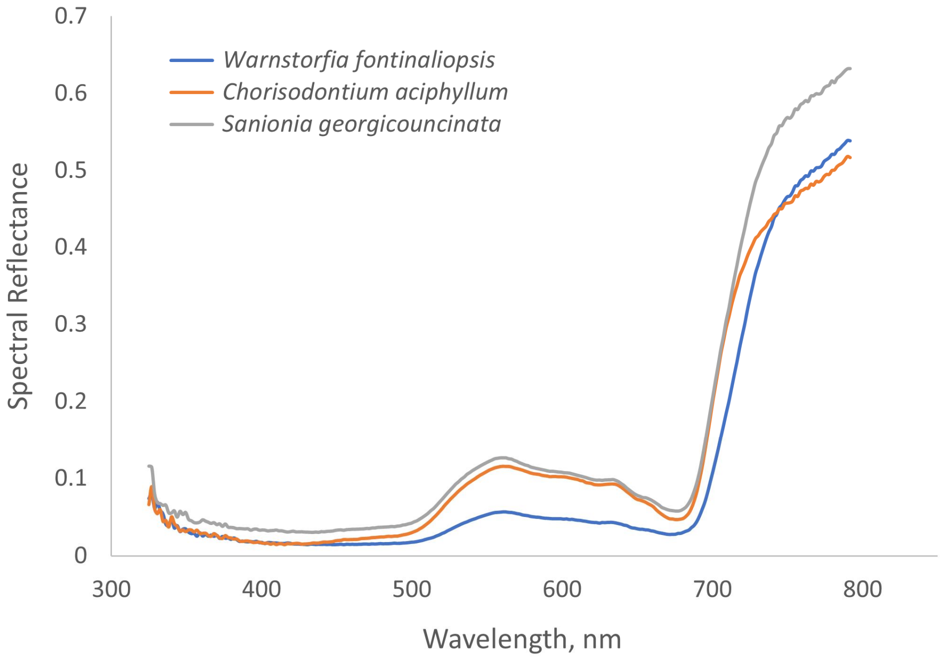

Fig. 1. Reflection spectra of mosses *W. fontinaliopsis, Ch. aciphyllum* and *S. georgicouncinata* measured by a PolyPen RP 410 UVIS.

Based on the data in Table 2, there are indices that do not differ statistically significantly between the studied species, those that also distinguish one of the studied species from the others, and finally, indices that are statistically significantly different for all studied moss species.

Indices without statistically significant differences between population was the only one: OSAVI.

Indices with statistical significant differences were: ZMI, Ctr2, SIPI, GM1, GM2, CRI1, and CRI2.

Indices that distinguished *W. fontinaliopsis* green state from other species studied were: NDVI, SR, MCARI, TCARI, PSNDa, ARI1, ARI2 (and ZMI, Ctr2, SIPI, GM1, GM2, CRI1, CRI2).

Indices that distinguished *Ch. aciphyllum* green state from other species studied were: SRPI, NPQI, NPCI, Ctr1 (and ZMI, Ctr2, SIPI, GM1, GM2, CRI1, CRI2).

Indices that distinguished *S. georgicouncinata* green state from other species studied were: MCARI1, TVI, PRI (and ZMI, Ctr2, SIPI, GM1, GM2, CRI1, CRI2).

Index	***Warnstorfia fontinaliopsis***	***Chorisodontium aciphyllum***	***Sanionia georgicouncinata***
NDVI	0.836 ± 0.066 [b]	0.687 ± 0.060 [a]	0.729 ± 0.058 [a]
SR	12.787 ± 4.341[a]	5.666 ± 1.507 [b]	6.664 ± 1.484 [b]
MCARI1	0.750 ± 0.203 [a]	0.742 ± 0.210 [a]	0.897 ± 0.110 [b]
OSAVI	0.790 ± 0.104 [a]	0.727 ± 0.080 [a]	0.772 ± 0.035 [a]
G	1.993 ± 0.339 [a]	2.536 ± 0.794 [b]	2.195 ± 0.248 [ab]
MCARI	0.273 ± 0.099 [a]	0.550 ± 0.213 [b]	0.433 ± 0.066 [b]
TCARI	-0.145 ± 0.054 [a]	-0.328 ± 0.179 [b]	-0.235 ± 0.041 [b]
TVI	27.322 ± 7.460 [a]	26.896 ± 7.761 [a]	33.005 ± 4.177 [b]
ZMI	2.456 ± 0.506 [c]	1.519 ± 0.113 [a]	1.848 ± 0.194 [b]
SRPI	0.489 ± 0.102 [b]	0.340 ± 0.088 [a]	0.526 ± 0.072 [b]
NPQI	0.043 ± 0.073 [b]	-0.068 ± 0.094 [a]	0.019 ± 0.041 [b]
PRI	-0.163 ± 0.045 [a]	-0.150 ± 0.035 [a]	-0.120 ± 0.025 [b]
NPCI	0.349 ± 0.094 [a]	0.498 ± 0.093 [b]	0.314 ± 0.063 [a]
Ctr1	4.670 ± 1.573 [a]	8.592 ± 1.620 [b]	4.584 ± 0.654 [a]
Ctr2	0.153 ± 0.062 [a]	0.289 ± 0.057 [c]	0.245 ± 0.047 [b]
PSNDa	0.882 ± 0.059 [b]	0.821 ± 0.051 [a]	0.825 ± 0.033 [a]
SIPI	1.047 ± 0.029 [a]	1.130 ± 0.050 [c]	1.085 ± 0.041 [b]
GM1	8.895 ± 2.225 [c]	4.292 ± 0.537 [a]	4.844 ± 0.728 [b]
GM2	4.576 ±1.342 [c]	2.369 ± 0.389 [a]	2.892 ± 0.450 [b]
ARI1	9.831 ± 3.923 [b]	4.738 ± 2.534 [a]	3.500 ± 1.014 [a]
ARI2	5.000 ± 1.222 [b]	2.192 ± 0.588 [a]	2.174 ± 0.500 [a]
CRI1	29.216 ± 7.207 [c]	16.298 ± 4.855 [b]	10.969 ± 2.829 [a]
CRI2	39.047 ± 9.032 [c]	21.036 ± 6.761 [b]	14.469 ± 3.722 [a]
RDVI	0.657 ± 0.116 [ab]	0.602 ± 0.095 [a]	0.676 ± 0.046 [b]

Table 2. Comparison of the spectral reflectance indices for studied moss species.

Discussion

Lovelock and Robinson (2002) found that moss species, as well as mosses from different microtopographic positions, varied significantly in their surface reflectance properties, however, different reflectance parameters were sensitive to different ecological or physiological factors. Also, it is known that moss tolerance to freezing in hydrated state ranged between different species (Perera-Castro et al. 2021). Previously we described (Puhovkin et al. 2023) that NDVI discriminates well between brown and green states of moss species of the Antarctic bryophyte carpet and mat subformation but it is not efficient to discriminate intermediate states. Complementary application of PRI appears to be promising for studies focused on the determination of the color differences attributed to ecolophysiological state of a moss community.

It is known that the NDVI is one of the indices most commonly used for mapping. NDVI for *W. fontinaliopsis* green state ranged from 0.61 to 0.91 with the mean of 0.836 ± 0.066 which is statistically significantly higher in comparison to same states of *Ch. aciphyllum* (0.58 to 0.81 with the mean of 0.687 ± 0.060) and *S. georgicouncinata* (0.59 to 0.81 with the mean of 0.729 ± 0.058). This means that NDVI can be used to distinguish *W. fonti-*

naliopsis from other studied species. These results are in good accordance with the data for *W. fontinaliopsis* and *S. georgicouncinata* from study of Puhovkin et al. (2023) on green state of moss cover. In this study 7 indices statistically significantly differed between studied species in green states (ZMI, Ctr2, SIPI, GM1, GM2, CRI1, CRI2). ZMI and GM2 have similar formulas using spectral reflectance (R) at 750 and 710 nm, and 750 and 700 nm, respectively. Similar to them is Ctrl2 which uses R695 and R760, and GM1 which uses R750 and R550. Carotenoid Reflectance Indices uses R510, R550 and R700 nm. Finally, Structure Insensitive Pigment Index is calculated based on R450, R650 and R790.

For the monitoring tasks, we used UAV with typical spectral bands: green (G) 550 nm ± 16 nm, red (R): 650 nm ± 16 nm, Red edge (RE): 730 nm ± 16 nm, and Near-infrared (NIR): 860 nm ± 26 nm.

Fresh results of Sandino et al. (2023) indicated the successful detection and mapping of mosses and lichens. In addition to the calculation of established vegetation indices, this study proposes the calculation of new spectral indices to aid the classification performance of moss-lichen models.

Taking into account the wavelengths of the spectral camera channels and the proposed indices from Sandino et al. (2023), additional indices are calculated in Table 3.

Index	***Warnstorfia fontinaliopsis***	***Chorisodontium aciphyllum***	***Sanionia georgicouncinata***
HSMI	0.822 ± 0.07 [a]	0.698 ± 0.08 [b]	0.732 ± 0.06 [b]
R730/R550	7.170 ± 1.541[a]	3.897 ± 0.465 [b]	4.188 ± 0.541 [b]
R790/R750	16.309 ± 5.704 [a]	7.480 ± 2.571 [b]	8.561 ± 2.068 [b]
R730/R650	11.375 ± 3.617 [a]	6.020 ± 2.122 [b]	6.660 ± 1.484 [b]

Table 3. Additional spectral reflectance indices for studied moss species.

Table 3 clearly shows that all these indices distinguish *W. fontinaliopsis* in green state from other species in the same state. But the difference between *Ch. aciphyllum* and *S. georgicouncinata* is not enough to distinguish between them.

Conclusions

We can conclude that spectral reflectance indices calculated at wavelengths typical of UAV spectral cameras can be potentially used to distinguish between different moss species within the same physiological state (green) in the same community.

Simple indices calculated as the ratio between the spectral reflectance in the green, red and red edge channels may be promising for further development of remote distinction of moss species as dominant components of terrestrial plant communities in the maritime Antarctic.

In conditions of Galindez Island moss bank, these indices distinguish well between *Warnstorfia fontinaliopsis* green state and same state of the other studied species, but in order to distinguish *Chorisodontium aciphyllum* and *Sanionia georgicouncinata*, it is necessary to use more sensitive indices or use UAV spectral cameras with more flexible channel selection.

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