Ecological Indicators 156 (2023) 111080

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Suitability and limitations of ground-based imagery and thermography for long-term monitoring of vegetation changes in Victoria Land (continental Antarctica)

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ARTICLE INFO

Keywords:
Climate change
Vegetation as bio-indicator
Field survey data
Ground-based remote sensing
Fishnet grid
RGB supervised
Growing season

ABSTRACT

Antarctic vegetation has been recognized to be a valuable bio-indicator to track climatic and environmental changes through an accurate long-term monitoring. The extremely harsh climatic conditions of Antarctica, its limited logistical accessibility and remoteness encourage the substitution or integration of field surveys with remote sensing monitoring.

Here we assess the applicability and limitations of ground-based remote sensing (visible imagery and thermography) for accurate long-term monitoring of vegetation changes in continental Antarctica with reference to: a) total vegetation coverage; b) cover of the dominant species; c) vegetation seasonality. We selected the three most widespread continental Antarctic vegetation types (high cover moss; low cover moss; low cover moss and/or lichen).

For the total vegetation cover the best fitting with the field data was achieved by the fishnet grid analysis performed by the expert and by the RGB_sup analysis, the two methods providing the highest feasibility, especially for the high cover moss, while for the other vegetation types the remote sensing methods provided over- and/or under-estimations (including GEI, differently from the Arctic).

Regarding the dominant species cover (%), none of the remote sensing methods provided suitable results, while we demonstrated that seasonality affects the quantification of total vegetation cover through remote sensing due to changes of vegetation temperature, hydration and activity, especially for moss vegetation, even analyzing mono-specific vegetation plots. This finding underlines the importance of the timing of the digital image acquisition, an issue that has never been addressed before in continental Antarctica.

1. Introduction

Climatic and environmental changes are rapidly modifying the fragile Antarctic terrestrial ecosystems (e.g. Gooseff et al., 2017; Robinson et al., 2018; Sancho et al., 2019; Cannone et al., 2021; Cannone et al., 2022), emphasizing the need for a timely and accurate monitoring to assess their changes, in particular for land cover and vegetation, as it has been recognized to be a valuable bio-indicator of climatic and environmental change (Green et al., 2011; Green et al., 2012; Robinson et al., 2018; Sancho et al., 2019). Vegetation changes may involve several characteristics useful for its long-term monitoring such as its type, total coverage, physiognomy, biodiversity, vitality and health.

Antarctica is characterized by climatic and environmental gradients allowing identify distinct biogeographical regions showing different biodiversity patterns, with sixteen biological distinct regions being identified as Antarctic Conservation Biogeographical Regions (ACBR) (Terauds et al., 2012; Terauds and Lee, 2016). Based on the prevailing growth form and community dominants, Antarctic vegetation is organized in two main vegetation formations: the Antarctic herb tundra formation, and the Antarctic non-vascular cryptogam tundra formation (e.g., Gimingham et al., 1970). In continental Antarctica only the non-vascular cryptogam tundra (characterized by the occurrence only of bryophytes, lichens, fungi and algae) occurs, in most cases with low and discontinuous cover (Kappen, 1985; Smith, 1988; Melick et al., 1994; Melick and Seppelt, 1997; Seppelt et al., 1995, 1996; Seppelt and Green, 1998). According to the dominance of different plant types, within the

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https://doi.org/10.1016/j.ecolind.2023.111080
Received 9 August 2022; Received in revised form 9 October 2023; Accepted 11 October 2023

Antarctic non-vascular cryptogam tundra formation three principal sub-formations were described (Smith, 1988, 1990): short moss turf and cushion sub-formation (dominated by mosses); foliose and fruticose lichen sub-formation (dominated by macrolichens); crustaceous lichen sub-formation (dominated by crustose and microlichens). Within each formation and sub-formation, identified according to the prevailing physiognomy and growth form, there are several vegetation communities characterized by different floristic composition, biodiversity and ecology (e.g. Smith, 1988; Melick et al., 1994; Melick and Seppelt, 1997; Seppelt et al., 1995, 1996; Seppelt and Green, 1998; Cannone and Seppelt, 2008; Cannone et al., 2018).

In Antarctica the extremely harsh climatic conditions, its limited logistical accessibility and remoteness encouraged the substitution or integration of field surveys with remote sensing monitoring based on different approaches, allowing the spatialization of data over large areas. Indeed, a large-scale deglaciation and increased air temperatures are predicted to affect in a short time the Antarctic continent (Noble et al., 2020). The availability of new bare grounds and a favorable climate will trigger large scale processes of vegetation colonization (Favero-Longo et al., 2012; Boy et al., 2016), following the recent trend of climate change acceleration (Cannone et al., 2022). As these fast changes are expected to occur over large territories, it will be mandatory to provide a long-term detailed monitoring of these changes. However, as it will not be possible to fully assess and quantify them through direct field investigations, hence remote sensing could allow to achieve rapid scientific data production over large and remote areas. The selection of the specific remote sensing sources, spectral range and resolution depends on the monitoring aims and objects (e.g., Turner et al., 2012, 2014, 2018; Jawak et al., 2015; Malenovský et al., 2017; King et al., 2020; Levy et al., 2020; Miranda et al., 2020; Power et al., 2020; Sotille et al., 2020). The available literature highlighted some limitations of these remote sensing techniques due to the low size and patchiness of the Antarctic vegetation and the difficulty to discriminate between vegetation types, in particular for lichen dominated communities (Jawak et al., 2015; King et al., 2020; Miranda et al., 2020; Sun et al., 2021). Moreover, the use of unmanned aerial vehicles (UAVs) in Antarctica could be rather difficult due to the harsh weather conditions (Dąbski et al., 2020), particularly aggravated in areas of continental Antarctica with dominant katabatic winds, where the helicopter survey is often the most suitable solution for mid-range remote sensing (Ponti and Guglielmin, 2021; Ponti et al., 2021).

In several parts of Antarctica, including also continental Antarctica, recent climatic and environmental change affected vegetation coverage, biodiversity (species richness) and vitality, with relatively fast changes requiring an accurate long-term monitoring (Cannone, 2004, 2006; Guglielmin et al., 2014; Pereira et al., 2018; Robinson et al., 2018; Cannone et al., 2021; Cannone et al., 2022). Remote sensing techniques through the use of UAV and/or digital image analysis provided a valuable contribution to assess changes in vegetation health and vitality although referred only to moss dominated vegetation (e.g., Malenovský et al., 2017; Turner et al., 2018; King et al., 2020), emphasizing the difficulties of analyzing macrolichen vegetation.

To our knowledge, in continental Antarctica the feasibility of remote sensing methods respect to the field survey to assess changes of floristic composition and dominance, and the impact of seasonality on the assessment of vegetation cover and dynamics has not been tested yet, despite understanding their changes is mandatory to assess properly the dynamics triggered by the ongoing and future climatic and environmental changes. This is of particular interest in order to understand the feasibility and limitations of vegetation remote sensing in such kind of harsh environments especially of continental Antarctica, to generate high quality, temporally dense datasets for identifying trends provided by vegetation as bio-indicator of climatic and environmental changes. Indeed, while these topics have been deeply assessed for the Arctic, where a number of research has already been conducted (Beamish et al., 2020; Nelson et al., 2022) and where the potential land ice cover loss and thus bare ground re-exposition is reduced respect to Antarctica (Lee et al., 2017), only few investigations addressed these topics for Antarctica.

Here, we aim to assess the applicability and limitations of ground-based remote sensing for accurate long-term monitoring of vegetation changes in continental Antarctica and, for this aim, we compare and quantify the feasibility of different analysis of RGB images respect to field survey with reference to: a) total vegetation coverage; b) cover of the dominant species; c) vegetation seasonality. In particular, a remarkable point of our work is the testing of simple indices that do not require multi-spectral sensors to assess the potential and limitation of remote sensing, as this simple tool could enlarge the remote sensing audience providing temporally dense datasets on vegetation trends, making the Antarctic vegetation remote sensing comparable with the methodology used in the Arctic regions (Anderson et al., 2016; Andresen et al., 2018; Richardson et al., 2018). For these aims we selected three case studies among the most widespread vegetation conditions typical of continental Antarctica (high cover moss vegetation; low cover moss vegetation; scattered lichen and moss vegetation) (Smith, 1988; Melick et al. 1994; Seppelt et al., 1995, 1996; Melick and Seppelt, 1997; Seppelt and Green, 1998; Cannone and Seppelt, 2008; Cannone et al., 2018) across an existing long-term monitoring network extended over latitudinal, geographical and ecological gradients in Victoria Land (continental Antarctica) since 2002/2003.

2. Methods

2.1. Study area

The study area is in Victoria Land, Ross sector, continental Antarctica, where since 2002/2003 a network for the long-term monitoring of vegetation, permafrost and climate was established across a geographical gradient encompassing five degrees of latitude between Apostrophe Island (72°S) and Finger Point (77°S) (Cannone, 2006; Cannone et al., 2013; Cannone and Seppelt, 2008; Guglielmin et al., 2014; Cannone et al., 2018; Cannone et al., 2021) (Fig. 1). Since 2014/15 the monitoring network has been implemented with a network of manipulation experiments to simulate the impacts of future climate change, included in the ITEX (International Tundra EXperiment) network (Cannone et al., 2021).

The climate of Victoria Land is frigid, with mean annual air temperature ≤ -14 °C (e.g. −17.7 °C at Marble Point, 77°S; −14.0 °C at Baia Terra Nova, 74°S; −15.6 °C at Cape King, 73°S) (Cannone et al., 2021).

The vegetation of Victoria Land is composed exclusively of cryptogams and it includes different vegetation communities dominated by a) moss vegetation, b) mosses encrusted by epiphytic lichens, c) foliose and fruticose lichens vegetation, d) microlichens, or e) scattered epilithic and epiphytic lichens and mosses (Cannone and Seppelt, 2008).

2.2. Field survey data

According to the minimum area requirements of the vegetation occurring in continental Antarctica, the size of the plots both for long-term monitoring and for the manipulation experiment is 50 × 50 cm (Cannone, 2004). The field survey was carried out integrating within each 50 × 50 cm plot three different survey methods at different scales (Fig. 2): 1) the phytosociological survey over the 50 × 50 cm plot, 2) the phytosociological survey carried out for each of the 100 cells of the 5 × 5 cm grid inserted within the 50 × 50 cm plot; 3) the point intercept at each of the 121 nodes of the 5 × 5 cm grid inserted in the 50 × 50 cm plot (Cannone, 2006).

For the comparison of the total vegetation cover (%), floristic composition, and species richness data provided by the field survey with those achieved applying the remote sensing techniques, the following case studies were selected as representative of the most widespread continental Antarctic vegetation: 1) high cover (≥50 %) moss

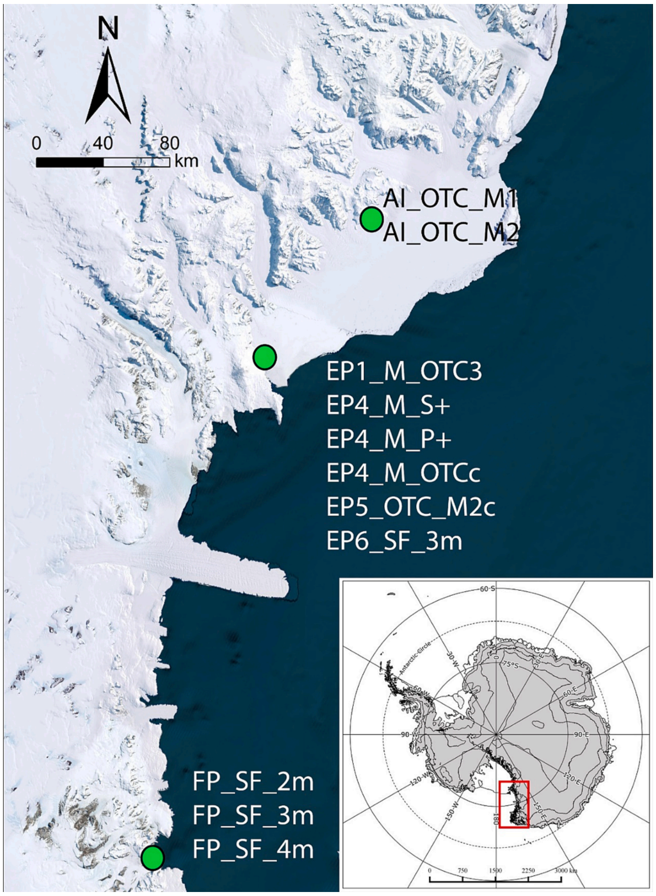

Fig. 1. Location of Victoria Land in Continental Antarctica and the positions/names of the vegetation plots at Finger Point (FP), Edmonson Point (EP) and Apostrophe Island (AI).

dominated vegetation; 2) low cover (50 % < cover ≤ 25 %) moss dominated vegetation; 3) low cover and scattered (<25 %) moss and/or lichen vegetation.

For each case study, three replications were selected. Only on the high cover moss dominated vegetation we added two further case studies to compare plots characterized by the occurrence of only one moss species (i.e., monospecific) versus plots with more than two moss species (plurispecific). Totally eleven different case studies were analyzed.

According to literature data, as macrolichen vegetation in Continental Antarctica is difficult to be analyzed through remote sensing (e.g. King et al., 2020), this vegetation type was not considered in the present study.

The field survey was carried out by one of the authors (NC) in January-February 2015, during the peak of the austral summer, according to the protocol described in Cannone (2006). The field survey data used for this study are the total vegetation cover (%) and cover (%) of the dominant species.

2.3. *Remote sensing analysis*

Digital RGB photographs of each quadrat were taken in January 2015 and December 2017. The images were taken with a nadiral position at ca. 1 m above the quadrat. The utilized camera was a Nikon D60 in 2015 (3872 × 2592 pixels) and an Olympus E-PL1 in 2017 (4032 × 3024 pixels).

The following digital image treatment permitted to extract the percent cover of the vegetation on the quadrat.

The fishnet grid method (Baxendale et al., 2016) was applied to compare the field data with digital RGB photographs of the plots: the RGB pictures of each selected plot were imported in a simple image displayer software and each plot was overlaid with a 5 × 5 cm cell grid, simulating the grid used in the field for the vegetation survey as in King et al. (2020). Then, the 100 5x5 cm cells of each plot were analyzed by the vegetation expert (NC) to compute the total vegetation cover and assess of the floristic composition and species richness of each 50 × 50 cm plot.

The second digital analysis was conducted in ArcGIS 10.8 (ESRI, Inc., Redlands, CA, USA). The nadiral RGB images were firstly imported as 3-band composite and, consequently, as single-band images with pixel integer values that ranged from 0 (black) to 255 (white). These latter were processed with the raster calculator tool to calculate the red ratio (rR), the green ratio (rG) and the blue ratio (rB) according to Beamish et al. (2016) following the formula:

$$rR = R/(R+G+B) \tag{1}$$

and similarly for rG and rB.

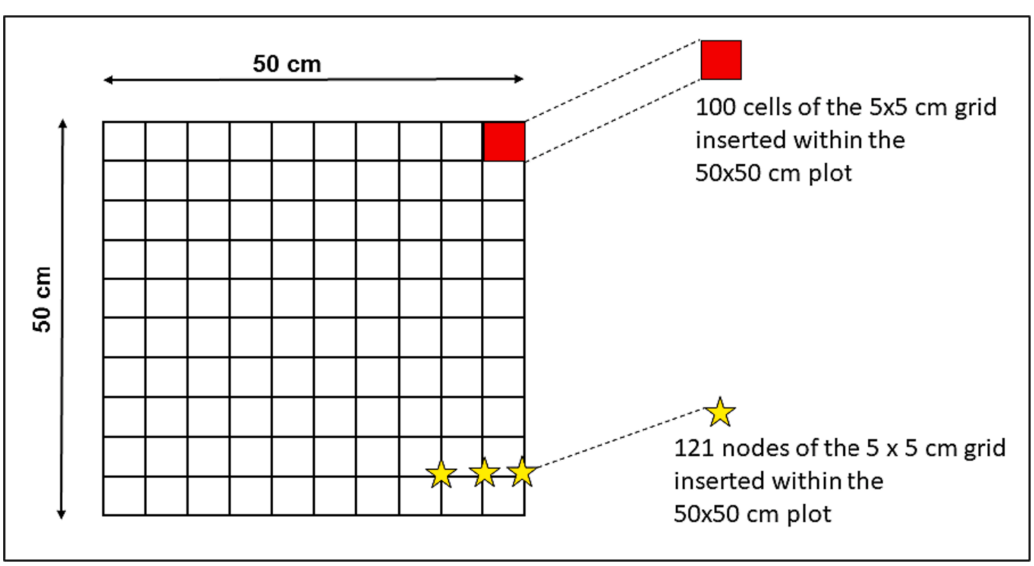

Fig. 2. Sampling design of the field survey for the assessment of vegetation cover (%), floristic composition and species richness within a 50 × 50 cm plot, according to Cannone (2004, 2006).

These ratios were then used to calculate the green excess index (GEI) (Richardson et al., 2007), a useful index used for vegetation phenology in the Arctic (Anderson et al., 2016; Andresen et al., 2018) that highlights the different brightness of the vegetation green according to the formula:

$$GEI = 2 * rG - (rR + rB) \quad (2)$$

Similarly, in order to highlight the redness of some lichens (i.e. *X. elegans*), a red excess index (REI) was calculated with the same formula but enhancing the rR instead of the rG. In this way, it has been possible to better individuate senescent (dry) to photosynthetically active mosses and lichens rather than the simpler RGB composites.

A supervised classification analysis (maximum likelihood classification) was run in ArcGIS on the obtained raster images for: a) the RGB composite (RGB_sup), b) the rG or rR (rGsup or rRsup) and c) the GEI or REI images (GEI_sup or REI_sup). The vegetation expert, who conducted the visual estimation of coverage in the field, spotted the presence of vegetation in ArcGIS and drew the region of interests (ROIs) on the RGB composites that corresponded to the bare ground or rock and a 100 % of vegetation coverage. A minimum of six polygons per class were drawn, randomly distributed, but choosing all the different tonalities of vegetation (from dark brown to light green) and bare ground to resemble all the available moss health conditions related to the seasonality during the Antarctic growing season (Sun et al., 2021). Indeed, since one of the aim of this paper is to quantify the total vegetation cover, we considered both healthy and unhealthy vegetation patches for the supervised classifications. Approximately, the area of the ROIs covered the 1 % of the total plot area. Consequently, the supervised classification was run by keeping the same ROIs for each image. In order to extract the total vegetation cover percentage of the classified image, a polygon of the plot was drawn and the number of classified pixels (vegetated and bare ground) were extracted and the ratio of the total number of the pixels in the polygon was computed to get the relative percentage.

Lastly, an automatic digital analysis (unsupervised classification) was conducted on the GEI images, as, according to Otsu (1979) and also Meyer and Neto (2008), the GEI well distinguishes the vegetation from the background if the threshold value is set to 0. We followed their method and, by reclassifying the GEI images, we obtained binary images of vegetation cover (positive values) and bare ground (negative values) for each quadrat.

To assess the effect of seasonality we selected the simplest case study, represented by a plot (EP4ms +) with 100 % moss vegetation cover with only one species, *Bryum argenteum*, as this species is easily identified through remote sensing. For this plot we analyzed the variation of the assessment of total vegetation cover (%) as provided using the RGB_sup method, of GEI, and of the surface temperature of 6 randomly chosen polygons across one growing season from late spring to the peak season (from 13/11/2018 and 15/01/2019), generally, when areas of Victoria Land are snow-free. This is the only available span of time for terrestrial ecologist to survey the exposed vegetation when snowdrifts do not occur.

The RGB camera utilized for this analysis was incorporated into the thermal camera FLIR E85 (1280 × 960 pixels), while the surface temperature of the plot was detected through the thermal sensor of the camera (384 × 288 pixels, 0.1 °C of resolution, 2 °C of absolute accuracy). The focal length of the camera did not permit to have perfectly nadiral images. However, the shooting position was kept constant and the resulting relative dimensions of the plot sectors comparable among the images. Indeed, percentages instead of absolute values helped in reducing the distortion errors.

Even though, at the timing of each acquisition a gentle breeze was present except on 10/01/2019, the wind uniformly reduced the heat flux of the plots starting from a stable situation in which the various surfaces (vegetation – bare ground) had different temperatures. As a result, both in presence or absence of breeze, the vegetation surface temperature, despite dependent on the weather conditions, is an indicator of seasonality or hydration.

All data provided by the remote-sensing analyses were compared with the data of the field survey of the same plots to quantify the suitability of the different approached used by remote sensing in providing data comparable with those achieved in the field. We tested through linear regression the statistical significance of the total cover (%) assessment by comparing the field survey respectively with: fishnet grid, RGB_sup, rGsup, GEI, GEI_sup. Moreover, we tested through linear regression also the statistical significance of the cover value provided by fishnet grid vs RGB_sup as well as of rGsup vs RGB_sup and of GEI vs GEI_sup. The mean absolute deviation (MAD) was also computed to assess the results deviation of the different survey methods.

Due to the low solar beams at these latitudes, the scattering of radiation produces mainly a diffuse light. Therefore, we did not consider to record the incident radiation at the time of shooting the photographs. However, we verified the quasi-constant light conditions of each survey (from 2015 to 2019) by calculating the standard deviation of the pixel DN of a portion of two clasts in the low cover moss plot. For R, G and B at all the dates, the standard deviation resulted to range between 7.2 and 12.7 that is quite low, indicating a very little change in light conditions during the surveys.

To highlight the different ability of the remote sensing techniques in assessing the vegetation cover, we computed the descriptive statistics (mean ± standard deviation ± 1.96*standard deviation) of total vegetation cover (%) and of the differences of total vegetation cover (%) of the three most widespread vegetation conditions (high cover mosses, low cover mosses, scattered moss and lichen vegetation), allowing the comparison of the feasibility of the different methods as well as providing a quantification of the confidence intervals.

Concerning the dominant species, we simply compared the values obtained by the field survey with those obtained by remote sensing (fishnet grid; RGB_sup; GEI_sup; rGsup; REIsup; rRsup). Lastly, to test the accuracy of the spatial distribution of the obtained results, we carried out a confusion matrix that considered both the total vegetation cover and the single species cover in a representative sub-quadrat of the study plot (i.e.10 × 10 cm) (Blatchford et al., 2021).

3. Results

3.1. Total vegetation cover

Independently from the vegetation type (high cover mosses, low cover mosses, scattered vegetation), the total vegetation cover (%) obtained by the different methods of remote sensing analyses exhibited statistically significant relations with the values obtained by field survey (Fig. 3). The best relations were obtained by the fishnet grid analysis performed by the expert followed by the RGB_sup analysis (Fig. 3). The root mean square error (RMSE) between the field coverage and the alternative methods showed good values: 10.8 % for Fishnet, 17.7 % for RGB_sup, 7.4 % for GEI_sup and 4.6 % for rGsup.

Moreover, the MADs of the vegetation types showed that the data are sufficiently variable with values ranging from 7.08 % (low cover mosses) to 12.17 % (high cover mosses) and deserve attention for the selection of the survey method (Table 1).

Analyzing separately each case study, the mean values of total cover (%) gave differentiated results. Indeed, while fishnet grid, RGB_sup and GEI (Fig. 4A, B) in the high cover moss were pretty similar to the field observation, the rGsup and GEI_sup showed huge errors. Considering the low coverage moss as well as the scattered lichen and moss vegetation (Fig. 4C-E) the quality of performance of fishnet grid and RGB_sup declined providing an under-estimation of the total cover, with the only exception of RGB_sup over-estimating the total cover of low cover mosses. GEI always provided a large over-estimation of the total cover both of low cover mosses as well as of scattered vegetation (Fig. 4C-E). On the contrary, fishnet grid, rGsup and GEI_sup provided an under-estimation of the total cover (Fig. 4C-E). These evidences were even

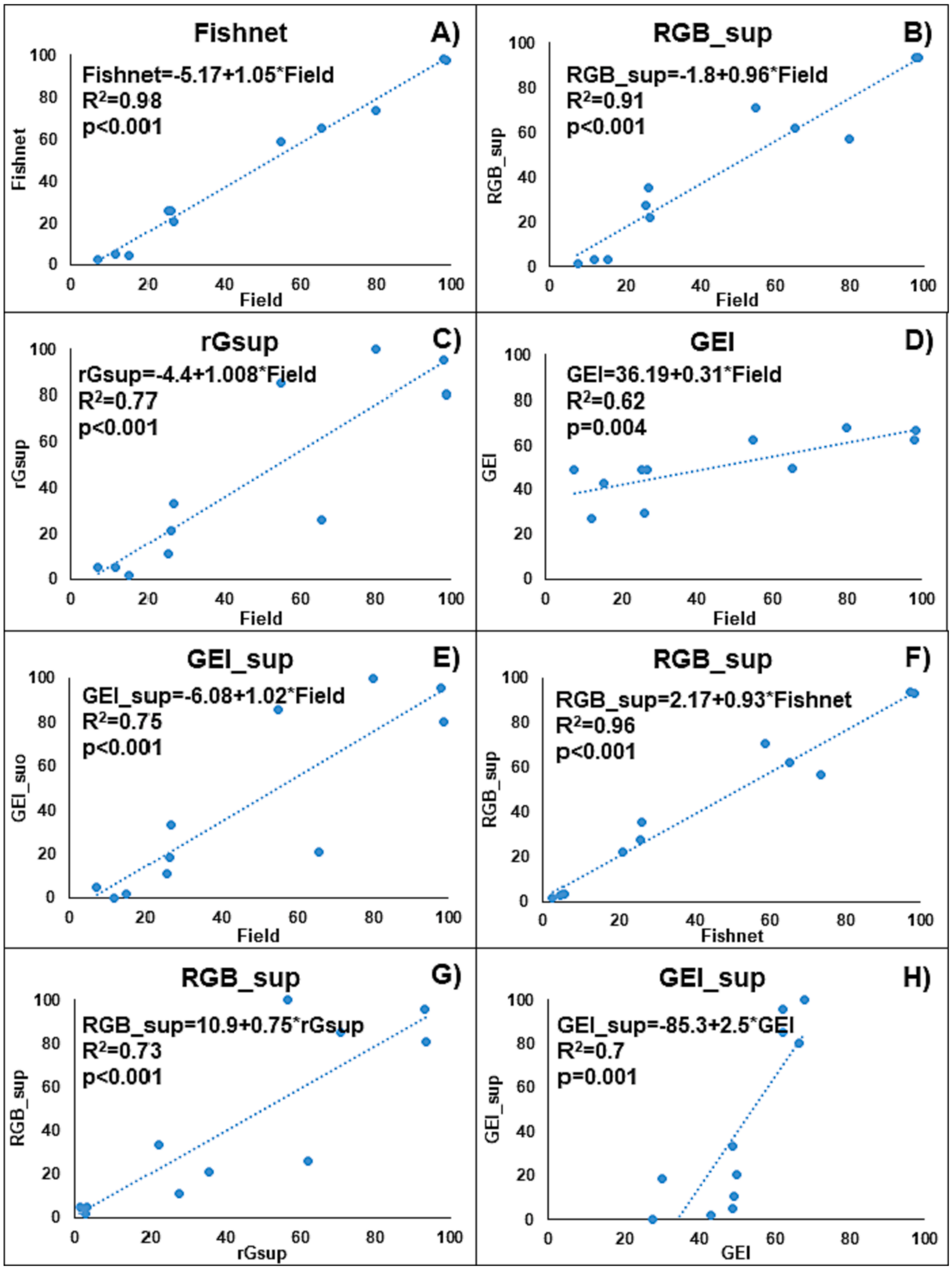

Fig. 3. Assessment of the statistical significance (tested by linear regression) of the total cover (%) assessment comparing: A) field survey vs fishnet grid; B) field survey vs RGB_sup; C) field survey vs rGsup; D) field survey vs GEI; E) field survey vs GEI_sup; F) fishnet grid vs RGB_sup; G) rGsup vs RGB_sup; GEI vs GEI_sup.

Table 1
Average vegetation cover percentage per vegetation type as quantified in the field and correspondent MADs.

	Field (%)	MAD (%)
High cover mosses	79.47	12.17
Low cover but continuous mosses	26.03	7.08
Low cover and scattered vegetation	11.44	10.41

more pronounced when considering the mean values of total cover and the mean of the differences of total cover of each method respect to the field survey (Fig. 4B, D, F).

The confusion matrix computed between the real ground coverage and the automatically assessed classes (presence-absence of vegetation) showed averagely good accuracies, without large differences between types of coverages (Table 2). Among all, the highest accuracy (how effectively pixels were grouped into the correct feature class) was obtained for RGB_sup (0.89) and the lowest for GEI (0.51).

3.2. Cover of dominant species

Concerning the quantification of the cover (%) of the dominant species, none of the remote sensing methods provided suitable results (Fig. 5), although some moss and lichen species were easier to be assessed through remote sensing like the lichen *X. elegans* (orange to red) or the moss *B. argenteum*, due to their color and growth form, making them easily recognizable from the other lichens and mosses (Fig. 5). On the contrary, in plots where there are different moss species with

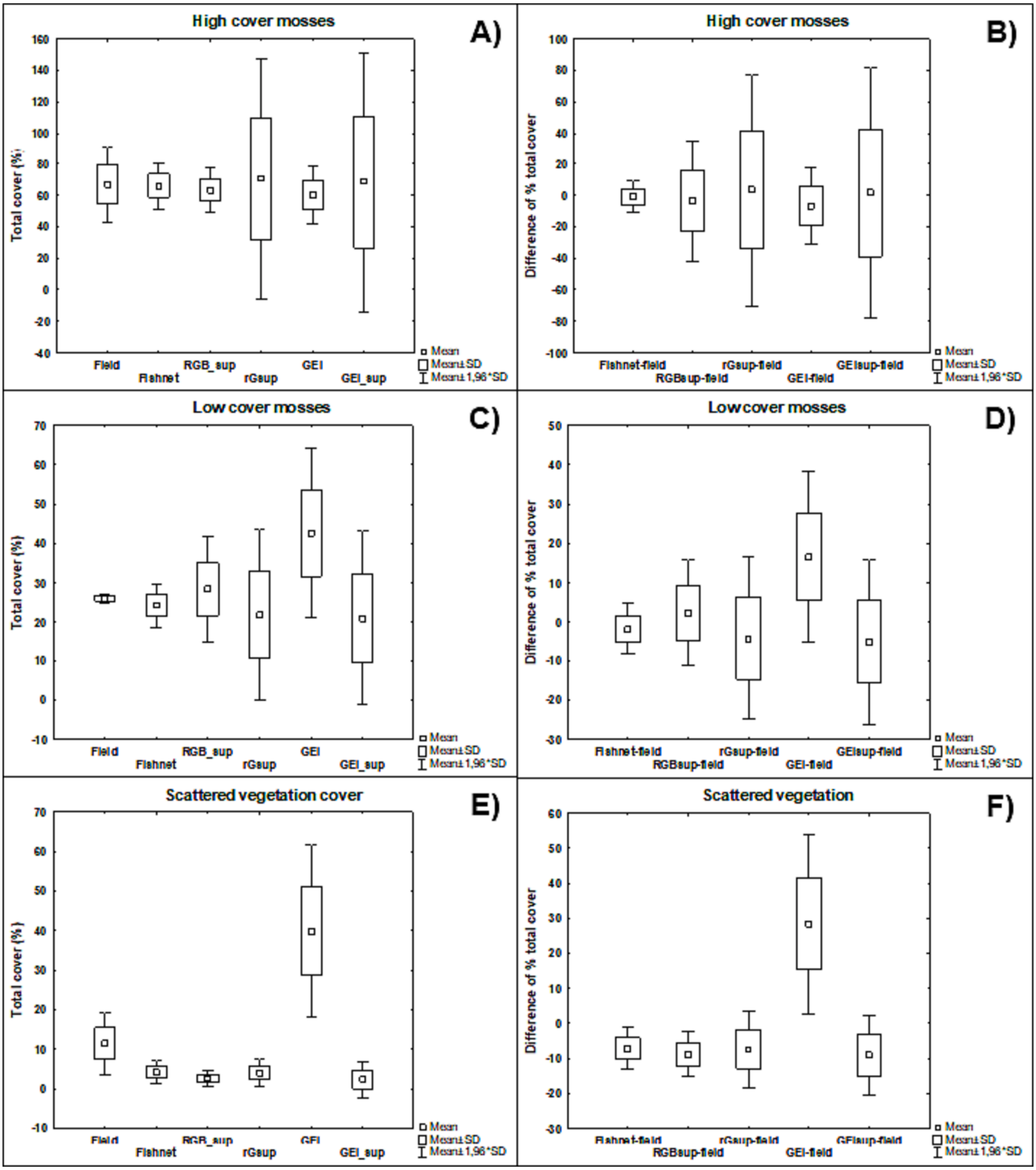

Fig. 4. Mean ± standard deviation ± 1.96*standard deviation of total vegetation cover (%) (A, C, E) and of the differences of total vegetation cover (%) (B, D, F) of high cover mosses (A, B), low cover mosses (C, D) and scattered moss and lichen (E, F) vegetation provided by the selected methods.

Cyanobacteria and/or epiphytic lichens, the quantification of the % cover of the different species is more challenging respect to the field assessment (Fig. 5). This difficulty is linked also to the hydration and health conditions of mosses and, within the same plot, their change during the growing season.

As an example of a plot representing a high cover mosses situation, Fig. 6 shows the differences of detection of the single moss species in the plot both with the supervised classification on GEI and on RGB images. From the visual estimation through the fishnet grid technique, this plot showed a floristic composition of *Bryum argenteum* (44.77 %), *B. pseudotriquetrum* (22.05 %), Cyanobacteria (15.97 %) and bare ground (20.31 %). The detection through the RGB_sup revealed a good agreement for *B. argenteum* (44.69 %), less for *B. pseudotriquetrum* (28.18 %) and bare ground (25.95 %), while worse for Cyanobacteria

Table 2
Accuracy values deriving from the confusion matrix computed between the real total coverage and the proposed methods. A = accuracy, k = Cohen's kappa score. Please note that background green refers to high cover mosses, yellow to low-cover but continuous mosses and orange to low-cover and scattered vegetation.

Plot name	RGB_sup		GEI_sup		GEI		rGsup	
	A	k	A	k	A	k	A	k
AI_OTC_M1	0.78	0.71	0.40	0.40	0.36	0.34	0.41	0.42
AI_OTC_M2	0.93	0.91	0.88	0.87	0.22	0.21	0.88	0.87
EP1_mOTC3	0.97	0.89	0.93	0.87	0.82	0.74	0.93	0.86
EP5_OTC_M2cc	0.59	0.52	0.62	0.53	0.50	0.49	0.62	0.53
EP6_SF_3m	0.91	0.62	0.37	0.35	0.51	0.50	0.40	0.38
EP4_M_P+	0.91	0.73	0.81	0.67	0.45	0.42	0.81	0.67
EP4_M_S+	0.89	0.60	0.87	0.61	0.84	0.56	0.73	0.64
EP4mOTCcc	0.93	0.57	0.70	0.65	0.60	0.54	0.70	0.65
FP_SF_2m	0.96	0.92	0.96	0.96	0.46	0.48	0.94	0.92
FP_SF_3m	0.91	0.83	0.87	0.86	0.35	0.46	0.87	0.86
FP_SF_4m	0.97	0.97	0.94	0.94	0.52	0.51	0.94	0.94
Mean	**0.89**	**0.75**	**0.76**	**0.70**	**0.51**	**0.48**	**0.75**	**0.70**

(1.15 %). On the contrary, the GEI_sup technique showed very discordant values: *B. argenteum* (24.94 %), *B. pseudotriquetrum* (15.8 %), bare ground (59.24 %), Cyanobacteria (0 %).

3.3. Effect of seasonality

The assessment of the total vegetation cover (%) using remote sensing techniques could be influenced also by their changes during the growing season, depending on their temperature, hydration and activity, especially for moss dominated vegetation. We tested this potential effect for the monospecific plot with 100 % vegetation cover of *Bryum argenteum*, during the growing season the total coverage assessed with the RGB_sup method ranged between 22.94 % and 41.29 %, while field data showed that no change of the total vegetation cover were detected. Similarly, both the surface temperature and GEI exhibited a large average seasonal variation (Table 3), the former between 0.04 and 0.15, and the latter between 1.0 and 16.2 °C. Moreover, there is no temporal relation between the presented variables, except for a couple of cases in which a high total coverage corresponded to high GEI (20/12/18) or to high surface temperature (10/01/19) (Table 3).

Fig. 7 shows the visible details represented in Table 3. In particular, it is possible to observe that, although the RGB image of the plot showed no vegetation cover changes during the season, GEI varied, especially highlighting the increase of negative values (bare ground) in the central part of the season and the increase of positive values (moss) during the last day. Moreover, the surface temperature not only varied during the season but, more importantly, showed a distribution pattern that did not follow the moss cover. Indeed, it should be expected that the vegetation in any case decreased the surface temperature due to the lower albedo and the water content. However, especially in 10/12/18 and 10/01/19, the surface temperature of the moss cover was the highest of the plot, ranging between 16.0 and over 40.0 °C. It is also important to notice that this temperature pattern, except for 15/01/19, did not coincide with areas either of high or low GEI values. This fact suggests that both the GEI and the surface temperature highlighted a spatial distribution seasonal pattern that was not consistent with the unchanged moss cover and, additionally, that those variations were independent one from the other.

4. Discussion

Climatic and environmental changes are now occurring rapidly even in continental Antarctica where, in one decade, total vegetation cover (%) exhibited significant changes in response to a slight air warming and active layer thickening, with a concomitant major change of soil chemical-physical conditions (Guglielmin et al., 2014; Cannone et al., 2021). These data highlight the need for an accurate long-term monitoring being able to detect small cover changes (<5%), as these changes in cover and/or species richness or dominance are representative of a major process occurring now also in continental Antarctica. Therefore, there is the urgent need to provide valuable remote-sensing methods to improve the accurate long-term monitoring and its upscaling to larger areas. In the Arctic region, vegetation remote sensing is well established thanks to the occurrence of a tundra vegetation with a larger species richness and cover of vascular plants and a wide range of different vegetation types (from discontinuous herbaceous tundra to continuous shrublands), as well as the spatial continuity of the Arctic tundra that provide a full vegetation mapping of the Arctic circle and even the logistical advantages provided by several research infrastructures (Beamish et al., 2020; Nelson et al., 2022). In continental Antarctica the same techniques used in the Arctic are not sufficient to provide a useful understanding of the vegetation change due to the reduced and patchy continuity of vegetation, which is mainly dominated by mosses and lichens, as well as the long satellite revisit intervals (King et al., 2020; Malenovský et al., 2017). Here we followed the recommendation to improve *in situ*-validated datasets (e.g. Beamish et al., 2020), providing a link between field observation and high resolution remote sensing (that is ground-based imagery) and, additionally, showing the feasibility and limitations of vegetation sensing in continental Antarctica. We thus provide a scientific advance in a poorly studied continent that it is not comparable with the Arctic studies (Beamish et al., 2020; Nelson et al., 2022).

4.1. Total vegetation cover

Our data demonstrate that, overall, there is a significant variation among the classification methods analyzed in this work (MAD between 7.08 and 12.17 %), showing that their use is not interchangeable and providing a quantitative assessment of their feasibility. Our data show that the expert estimation of vegetation cover at the terminal (fishnet grid) is the remote method with the highest consistency with the field estimation, followed by the supervised classification of the RGB images, when applied to the whole set of case studies (Fig. 3). These methods well approximate the field estimation ($R^2 > 0.91$) and show a little deviation from the absolute percentage cover values (beta similar to 1) (Fig. 3). This is surprisingly important in the semi-automatic supervised classification: it is rare to find pixel-wise classification with high accuracy (Jawak et al., 2019), especially with different spatial pattern of vegetation cover. The reclassification conducted on rGsup and GEI indices did not show appreciable results probably because the 0 value, set as vegetation presence threshold, works well for vascular plants of mid latitudes (Meyer and Neto, 2008), but not with the moss and lichen dominated vegetation occurring in Antarctica. Moreover, a monochromatic 32-bit image, albeit derived from R + G + B channels that highlight vegetation on 3 different bands, showed a weaker detection property that lays in a missing-a-priori knowledge input of the surface (Xie et al., 2008). This is also true for the supervised classification run on the GEI because Antarctic mosses and especially lichens are not often

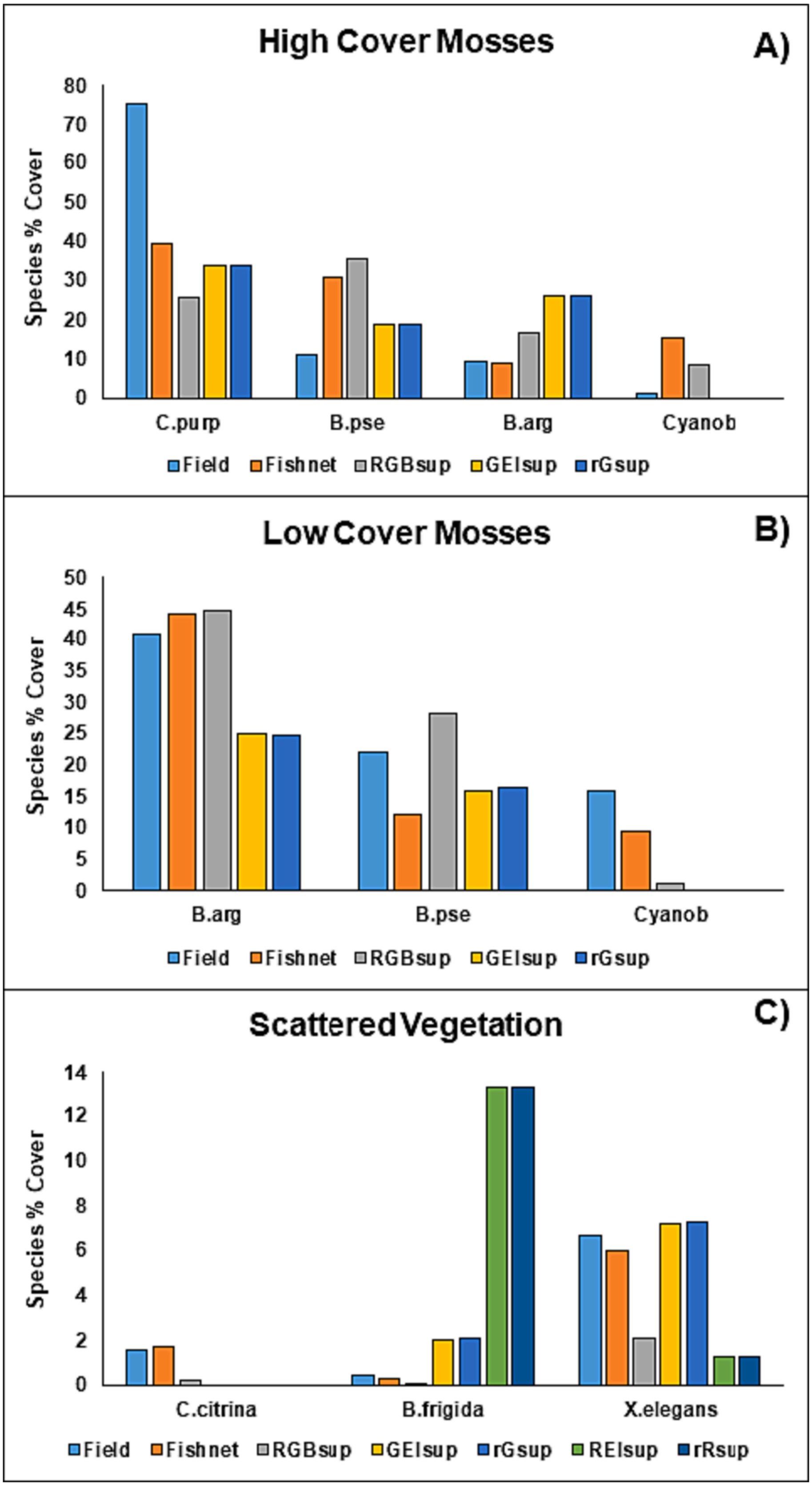

Fig. 5. Different results of the assessment of species cover (%) of the dominant species obtained comparing the field survey with the remote sensing techniques. Legend: field survey = pale blue; fishnet grid = orange; RGB_sup = grey; GEI_sup = yellow; rGsup = blue; REIsup = green; rRsup = dark blue.

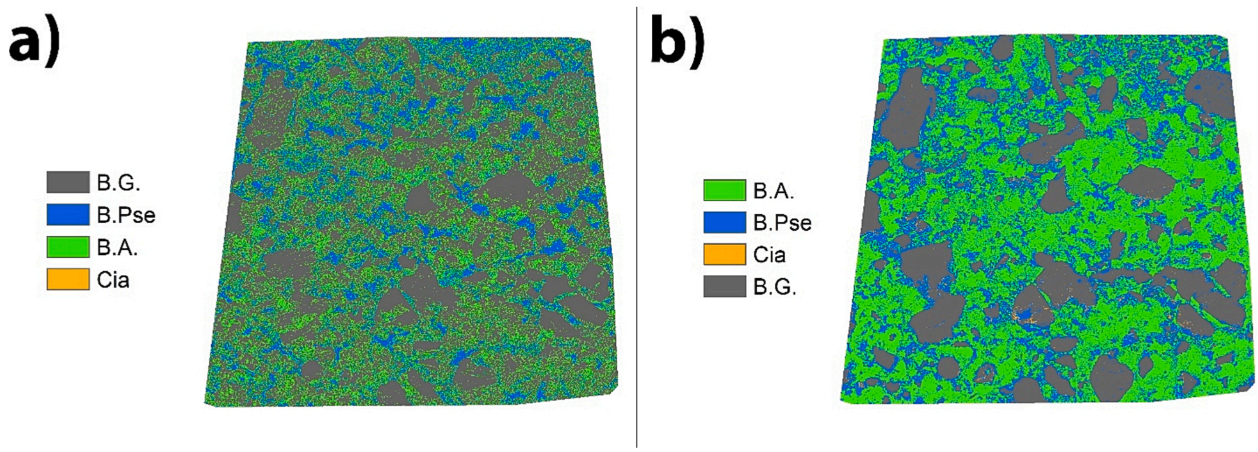

Fig. 6. Biodiversity classification in the study plot EP6 (2015, high cover moss): a) supervised classification run on the GEI, b) supervised classification run on the RGB image. B.A = *B. argenteum*, B.Pse = *B. pseudotriquetrum*, Cia = cyanobacteria, B.G = bare ground.

Table 3
Average value of GEI and surface temperature (°C) of six randomly chosen polygons of 100 % moss coverage at EP4ms + in different moments during the growing season. The last row refers to the total plot coverage assessed via RGB-sup digital analysis. Missing data are showed with "NA".

	13/11/2018	03/12/2018	10/12/2018	20/12/2018	31/12/2018	10/01/2019	15/01/2019
Local Time	09:56	09:32	15:02	15:34	07:55	14:55	15:45
GEI	0.05	0.04	0.06	0.15	0.06	0.04	0.05
Temperature (°C)	1.5	2.5	1.7	1.6	2.4	16.2	1.0
Total plot coverage (%)	22.94	NA	NA	37.95	28.31	41.29	36.32

green. This depends on their health status and pigment colors, therefore other spectral bands are needed (Calviño-Cancela and Martín-Herrero, 2016; Váczi et al., 2020; Jawak et al., 2019; Turner et al., 2018; Sun et al., 2021), also to highlight them from the background (Miranda et al., 2020; Sun et al., 2021).

We therefore show that, in presence of the only RGB channels (visible bands), it is difficult to automatically estimate the vegetation cover in Antarctica (threshold value detection). Rather, a semi-automatic method like the supervised classification is more indicated. In this view, classification algorithms are still dependent on the operator's input and cannot work independently. Since one of the aims of this study was to verify the vegetation cover estimation with remote sensing techniques, we kept the operator's input in the supervised classification very low (1 % of the total area) providing interesting results. Of course, more accurate/larger ROIs would likely have produced even better results (Xie et al., 2008), but this effort would have made the supervised classification more similar to the fishnet grid analysis.

To our knowledge, this is the second experiment using GEI in terrestrial ecosystems of Antarctica (Váczi et al., 2020). Unfortunately, this index did not work in this kind of environment because vegetation is not vascular and is strictly dependent on soil moisture, affecting the health status of mosses and, in turn, their color (Váczi et al., 2020; Malenovský et al., 2017; May et al., 2018; Waterman et al., 2018). Conversely, in the Arctic, GEI is well known to work even with the phenology of vascular species (Beamish et al., 2016; Andresen et al., 2018).

The average vegetation cover difference between the field observation and the fishnet grid was little because the expert knew what to observe even at the terminal. Interestingly, a little difference was obtained also with RGB_sup, suggesting that the expert's opinion in the ROIs definition is necessary (King et al., 2020). However, even the observation at the terminal can deviate from the original estimation *in situ* for the scattered vegetation environment (Fig. 4). For instance, both the fishnet grid and RGB_sup showed a similar deviation from the average field observation. It is probable that some lichens were better highlighted in the photographs respect to the field, during which the concentration of the expert can be demanding and not well performing after hours (King et al., 2020) or the weather at the observation time was not indicated (Bennett et al., 2000; Gorrod and Keith, 2009). Our data suggest that the use of remote sensing methods, in particular of fishnet grid and RGB_sup (providing the best agreement with field data), is recommended only for high cover moss vegetation, allowing to use these methods as substitute of field survey, while for the other vegetation types all remote sensing methods showed large errors and differences respect to the field survey (Fig. 4).

4.2. *Cover of dominant species*

The dominant species classification showed that there are differences even between the field and the fishnet grid observation, probably due to the different color representation *in situ* and on a terminal display (Kolyaie et al., 2019). It is also important to underline that the classic pixel-based classification that considers only the band reflectance hardly discerns the species composition because of their health status that lets the color have many shades. Therefore, for an algorithm (but also for an operator in front of a display) it is difficult to set the proper species threshold shade of a color due to its variable perception (Brown and MacLeod, 1997; Abramov et al., 2012).

The fact that for plots with low cover of mosses there is a similarity between field data and RGB_sup for *B. argenteum* could lay on the insolation of the moss patches and their different color. Indeed, a higher contrast is guaranteed between the bare ground and the vegetation in low covered plots compared to high covered plots. This helps the algorithm (and the operator) to distinguish the moss species that also exhibit a different color depending on their hydration and health status. *B. argenteum* is well recognizable given its color and shape, being very different from those of the other moss species occurring in continental Antarctica (e.g., Ochyra et al., 2008). Indeed, in the harsh conditions of continental Antarctica, it has been demonstrated that moss species detection could be accomplished only with hyperspectral analyses emphasizing species-specific differences not only related to pigments but also morphology of moss leaves (Lovelock and Robinson, 2002).

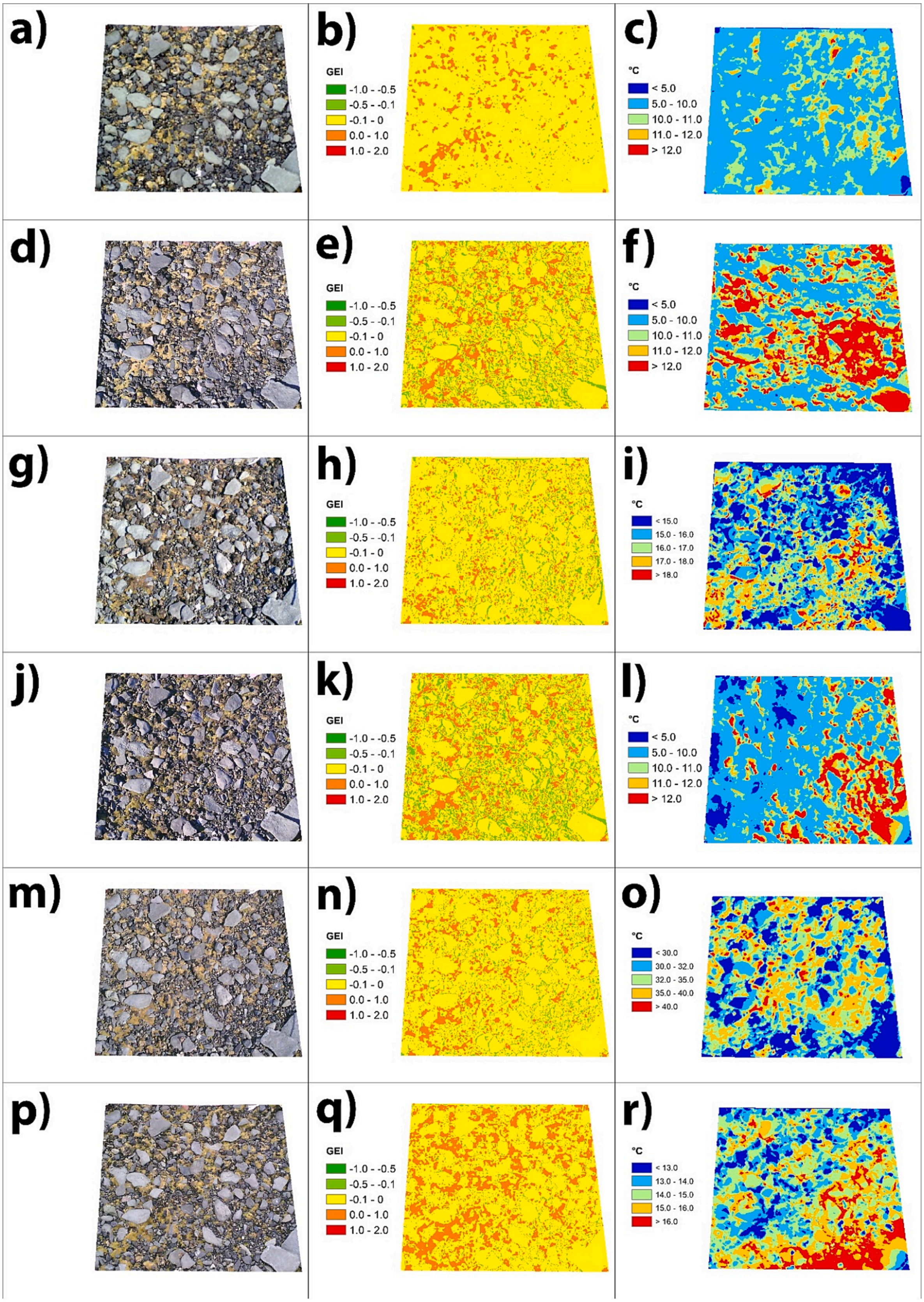

Fig. 7. Seasonal differences of RGB, GEI and surface temperature (°C) obtained from a low cover moss. a) RGB image of 13/11/18, b) GEI values of 13/11/18, c) surface temperature of 13/11/18, d) RGB image of 03/12/18, e) GEI values of 03/12/18, f) surface temperature of 03/12/18, g) RGB image of 10/12/18, h) GEI values of 10/12/18, i) surface temperature of 10/12/18, j) RGB image of 31/12/18, k) GEI values of 31/12/18, l) surface temperature of 31/12/18, m) RGB image of 10/01/19, n) GEI values of 10/01/19, o) surface temperature of 10/01/19, p) RGB image of 15/01/19, q) GEI values of 15/01/19, r) surface temperature of 15/01/19.

Many studies have claimed that the use of the NIR band could be a good way to reach the spectral signature of single species in Antarctica (e.g. Jawak et al., 2019; Váczi et al., 2020; Calviño-Cancela and Martín-Herrero, 2016). However, the resolution of NIR indices, the spatial distribution of the species/patches, the hydration/health status and the photosynthetic activity produce an inter/intra annual variability (Váczi et al., 2020; May et al., 2018; Jawak et al., 2019) that is difficult to standardize for a long-term monitoring. Moreover, the mixed pixel is a problem at any resolution (Sun et al., 2021; Fretwell et al., 2011; Jawak et al., 2019; Sotille et al., 2020).

Some RGB indices like RGBVI could exert significant results for vegetation species mapping (Váczi et al., 2020), while NDVI could not be exact in cryptogamic species detecting (Sotille et al., 2020; Fretwell et al., 2011; Casanovas et al., 2015), rather it is more useful for the photosynthetic status (Váczi et al., 2020; Calviño-Cancela and Martín-Herrero, 2016).

4.3. Seasonality

The seasonality of a single moss species has displayed a very variable assessment of GEI, surface temperature and total coverage. This fact is remarkable considering that the total vegetation coverage of each plot cannot vary more than the human error of estimation during one season (few weeks). The encountered issue is explainable by the fact that both the moisture and temperature of mosses is dependent on single weather-related events, such as cloudy or sunny conditions, wind speed or water availability due to snow patches melting. Indeed, it has been demonstrated that mosses can change rapidly their hydration state (with potential water loss exceeding 50 % of the water content in less than 100 min, e.g., Gimingham and Smith, 1971) and fastly recover from desiccation in less than 24 ours (e.g. Proctor et al., 2007) although with species-specific patterns, depending on their water retention capacity and ecology (e.g. Hrbáček et al., 2020). These characteristics allow mosses and lichen to adapt and persist in response to the climatic and environmental changes (air and soil temperature and moisture, wind, snow cover) affecting the site micro-edaphic conditions and occurring during the short growing season (lasting 1–4 months during the austral summer) (e.g., Melick and Seppelt, 1997). Therefore, single-days environmental situations can change the hydration state and the photosynthetic rate of mosses and also their color (Melick and Seppelt, 1997; Robinson et al., 2018; Hrbáček et al., 2020), thus affecting also the digital values of the image pixels. As a consequence, every day is able to show different GEI or temperatures depending on the moss hydric status or the weather conditions. This has direct effects on the digitally assessed total coverage that, in turn, changed greatly during the season (Table 3) (Jawak et al., 2019).

This consideration introduces a discussion on the perfect timing of the digital image acquisition that has never been addressed before in continental Antarctica, but could be a key point for the acquisition of the most suitable images. Indeed, due to the close-range topographic/environmental variability, it is difficult to suggest whether the beginning, the mid or the late season image acquisition would give the same results of a direct visual estimation. Definitely, we underline the importance of the plot scale variability, that, even with other multi-spectral sensor, is hard to fully explain and standardize for larger and correctly-interpreted aerial surveys. Indeed, it has been demonstrated that mosses can change their health status with a localized spatial variation due to the microhabitat moist conditions (Robinson et al., 2018). We therefore show that the spatialization of moss health status or cover in harsh environment could be treated remotely, but field checks are needed to assess misclassified areas. These can depend on the unchanged microtopography (so defined with increased temporal resolution of surveys) or the temporal variation of edaphic factors (for instance the anticipated or postponed snow melting or its magnitude of accumulation).

5. Conclusion

This study treated one of the main issues concerning vegetation remote sensing, that is the reliability of the digital analysis for detecting changes in vegetation cover, composition and seasonality. Based on a very close-range and simple RGB indices calculation, our data contributed to fill the gap between the *in situ* and remote survey of one highly heterogeneous and discontinuous vegetation growing in continental Antarctica.

The vegetation cover is still highly dependent on the operator's interpretations: indeed, only with the fishnet and the supervised RGB methods we obtained a good assessment of the high coverage sites, probably due to the fact that even at the terminal, only the vegetation expert is able to see the different tonalities and health status of vegetation based on visible bands. For the detection of dominant species, the same issues rose: the different coloration of the same species depending on the moisture availability or health status did not permit to have comparable results with the field observation. The assessment of species seasonality is even more inaccurate because both GEI and the surface temperature are extremely variable based on the physiological response (hydration state and photosynthetic activity) of mosses and lichens to the weather conditions that can change every day (snow melting and moisture availability, incoming radiation, wind speed).

Our data show that remote sensing in Antarctica for vegetation science could be a feasible tool to extensively map large areas, but the calibration/validation of a terrestrial ecologist's interpretation is mandatory. This interpretation can be achieved by the expert only if the imagery resolution is high enough to recognize the floristic composition (i.e. a ground-based remote sensing technique). Indeed, extensive mapping of vegetation through mid- to long- range remote sensing in Antarctica (UAVs or satellites) could end up in large approximations that are not useful to substitute the fieldwork of a vegetation ecologist. The feasibility of the methodology is maintained both at close- to long-range, but one should define in advance what is the aim of the study which may range from an extensive mapping for a rough quantification of the cover change to a reduced mapping at high details for the detection of species-specific interactions (Fretwell et al., 2011; Jawak et al., 2019; King et al., 2020). Moreover, the easiest and visible-band indices that are used in the Arctic did not work in continental Antarctica because of the patchiness of vegetation and large occurrence of lichens that are not green but are a key component of the colonization process as consequence of the climatic change. Hence, we recommend to develop experimental designs that include the *in situ* calibration coupled with multiple surveys during the season to avoid misinterpretations related to the variability of edaphic factors and the effect of seasonality.

CRediT authorship contribution statement

N. Cannone: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **M. Guglielmin:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **S. Ponti:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nicoletta Cannone reports financial support was provided by Programma Nazionale di Ricerche in Antartide (PNRA).

Data availability

Data will be made available on request.

Acknowledgments

This work has been supported by the Programma Nazionale di Ricerche in Antartide (PNRA) and funded by the projects PNRA 2013/AZ1.05 "Permafrost ecology in Victoria Land"; PNRA16_00194-A1 "Climate Change and Permafrost Ecosystems in Continental Antarctica"; PNRA18_00186-E" Interactions between permafrost and ecosystems in Continental Antarctica.

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