Moss bank composition on the Galindez Island (Argentine Islands): what it signifies?

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Abstract

Tall moss turf subformation, whose developed forms are called moss banks (MB), play an important role in the structure of vegetation communities in the maritime Antarctic. In the present research, we studied the spatial distribution, moss banks thickness, area, species amount, dependence between these parameters, and species composition of the 44 MB on Galindez Island, Argentine Islands, Graham Coast. To select indicators for the monitoring of communities affected by climate change and biotic disturbance we compared the key parameters of the largest moss bank on Galindez Island (Smith moss bank) with measurements received for this moss bank 46 years ago. Galindez moss banks' bryophyte flora included 13 species of mosses and three species of liverworts. There was no correlation between the species richness and the area of MB, but the species richness positively correlated with moss banks' thickness. We supposed species diversity of MB depended presumably on the age of the moss bank and micro-conditions than on the area. Abundance of some moss species correlated with moss bank thickness. A comparison of results obtained in this study and in 1976, revealed an increase in the amount of brown- and black-coloured curtains of *Polytrichum strictum*, no significant changes in the ratio of *Chorisodontium aciphyllum* and a decrease in the lichen incrustation. These results show that the ratio of *P. strictum's* colour morphotypes, *C. aciphyllum* and liverworts' abundance can be used to evaluate the condition of MB in the long-term monitoring.

Introduction

The maritime Antarctic is the most biologically rich part of the white continent and harbours a diverse cryptogamic flora that dominates in humid wind-protected habitats (Longton 1967; Gimingham et al. 1970; Ochyra et al. 2008; Hughes et al. 2020). Tall moss turf subformation, whose developed form is called moss bank (MB), is among notable cryptogamic communities, that are distributed only in the part of maritime Antarctic's region. Tall moss turf subformation is composed of either one or two core species capable of peat accumulation: *Polytrichum strictum* Brid. and *Chorisodontium aciphyllum* (Hook.f. & Wilson) Broth. On average, developed moss turf subformations are 1–2 m deep, and composed of the moss species in uneven ratios. The peat in the moss banks is accumulated in aerobic conditions almost without access to water: the mean annual level of water accumulation is 1 mm, which is approximately half of the annual moss biomass gain (Fenton 1982).

These communities host a number of other organisms in the maritime Antarctic (Smith et al 1979; Fenton and Smith 1982; Ochyra et al. 2008; Parnikoza et al. 2018). Surface of the moss bank increases the number of sites appropriate for plants' colonization, which mediates the growth of the other plants species. Cavities and roughness on the surface of the MB provide wind-protected sites that are appropriate for vegetation of plants that are more sensitive to environmental conditions. Moreover, MB protects the places of their development from wind erosion (Smith 1972; Collins 1976; Fenton 1982).

Tall moss turf subformation is distributed from 51°S (the Falklands Islands) to circa 69°S (Antarctic Peninsula). The most diverse and most developed examples of Tall moss turf subformation are abundant in the maritime Antarctic, especially in the South Orkney Islands area (Fenton and Smith 1982; Van der Putten et al. 2009; Convey et al. 2011).

P. strictum was one of the first bryophytes collected in Antarctica and described as *P. antarcticum* by J. Cardot (1907). According to Ochyra et al. (2008), P. *strictum* is distributed from the South Sandwich Islands to the Fallières Coast, and *C. aciphyllum* is found as far South as the Green Island (Graham Land, 65 °S). The core moss species are typical on the South Sandwich Islands, South Orkney Islands, the South of the Danco Coast and some offshore islands, in the most southern localities in Marguerite Bay, and the Alexander Island. In contrast, they are very rare on the South Shetland Islands and the northernmost of the Antarctic Peninsula. Fragments of the community can be found as high as 400 m a.s.l., yet they accumulate peat in the lower protected sites. The fragments of the community on the Signy Island and the Elephant Island are estimated to be 5500 years old (Björck et al. 1991; Ochyra et al. 2008).

Despite the abundance and ecological role of moss banks, there is a lack of information about communities' characteristics, patterns of occurrence and the diversity of the dependent species for most Antarctic regions. There is a clear lack of detailed present-day descriptions of the moss banks located in different parts of their distribution area. The first photos of these communities were recorded during the second Jean-Baptiste Charcot expedition, Petermann Island and Argentine Islands (Cardot 1913). Moss banks of the South Georgia (Fenton 1982) and the South Orkney Islands (Cannone et al. 2017) are the most studied. The first registration of the species that form MB in the Antarctic was made by E. Racoviţă (Cardot 1907), and in the Argentine Islands these species were registered by L. Gain in 1909 (Cardot 1913). Some knowledge relevant to the MB of the Argentine Islands can be gained from a number of studies provided by Smith and Corner (1973), Fenton and Smith (1982), Yu et al. (2016) etc. Bjorck et al (1991) provide information about the moss banks on the South Shetland Islands, and Convey et al. (2011) apprise details about moss banks on the Alexander Island. Some information about the MB on Signy Island is provided by Fenton and Smit (1982) and Cannone et al. (2017). Recently some details about the moss banks on the Argentine Islands also was published by Parnikoza et al. (2018).

The Polar Regions, and especially the maritime Antarctic area, experience the widest temperature fluctuations over the last fifty years (Convey et al. 2005; Turner et al. 2005), which affects on the distribution and condition of the vegetation. Gentoo penguins' (Pygoscelis papua Forster) nesting sites occur on the Galindez Island, which is almost the southern limit of the gentoo's Antarctic breeding range. Their nesting population on the Island is rapidly increasing and occupies new territories. The growing anthropogenic impact is another reason for the regular monitoring of the vegetation cover on the island (Yevchun et al. 2021).

Considering the above, selection of the vegetation indicators that illustrate the reaction to the environmental change in the region is crucial. *Deschampsia antarctica* È. Desv. has already been observed as an indicator on the Galindez Island (Parnikoza et al. 2011, 2018). The other studies evidence that moss banks can also be considered in this role (Kanda and Inoue 1994; Yu et al. 2016; Robinson et al. 2018). The large areas of homogeneous moss banks' communities are accessible for mapping which makes them a handy monitoring object. Moreover, they have shown a clear reaction to climate change. According to the study by Yu et al. (2016), they were sensitive to the warming in the past (the intensity of the mosses' growth follows the change in temperature and humidity).

Kanda and Inoue (1994) showed that moss banks can be used as an indicator at short timescales when estimating the number of the invasive species on their surface (e.g., primary thalli of lichens, algae or cyanobacteria). Long-term monitoring falls into place when complemented by evaluations of physical and environmental conditions. The mosses' growth rate is known to be dependent on the availability of water (Smith 1988; Forbert 1996). Robinson et al. (2018) studied the possibility of using some typical bryophytes tolerant to long droughts as the indicators (both qualitative and quantitative) of climate change in West Antarctica.

Protection is another argument to study the composition and parameters of the moss banks (Yevchun et al. 2021). It allows focusing on the most diverse or valuable vegetation covers.

In the framework of this research we aimed i) to study the spatial distribution and MB parameters as thickness, area, bryophytes' presence, incrustation, the correlation between these parameters, relative abundance (ratio) of brown and black *P. strictum* and species composition of the moss banks on Galindez Island; ii) to estimate parameters that can be used as indicators for monitoring of the communities affected by the rapid climate change and penguins' colonization.

Materials And Methods

Research area

The research was provided on the Galindez Island, which is the central island of the Argentine Islands group located in the Argentine Islands-Kyiv Peninsula region in the northern part of Graham Coast. Here, on Galindez Island, Ukrainian Antarctic Station "Akademik Vernadsky" is located. The study was realized during the summer seasonal expeditions in 2013–2022. During the seasons in 2013/14 (18 Ukrainian Antarctic Expedition), 2015/16 (20 UAE), 2018/19 (24 UAE), and 2019/2020 (25 UAE) we used a manual GPS navigator GPSMAP 66s to map 44 relatively large fragments of Tall moss turf subformation interpreted here as moss banks.

Notably, the literature lacks clear criteria to delineate a MB within fragments of this formation. Holdgate (1964) defined extensive closed stands of carpet- and turf-forming mosses locally covering relatively large areas, i.e exceeding 100 m^2. Fenton and Smith (1982) define 'moss peat bank' exactly as the *P. strictum* – *C. aciphyllum* variety of Tall moss turf subformation. In our work, we applied the term "moss bank" to all relatively big fragments of Tall moss turf subformation with 7 cm thickness and more.

Mapped MB were assigned with numbers (Fig. 1). We measured visualized area of every MB from the satellite images with the help of the Q-gis software. This software was also used for mapping.

Measuring parameters of moss banks

Thickness of a MB over the bedrock was determined with a metallic probe.

We recorded the abundance ratio (%) of areas occupied by differently coloured tufts of dominant species *P. strictum*: green-, brown- and black, as it was done by Fenton and Smith (1982). We estimated the occurrence of the co-foundation species *C. aciphyllum*, which is a percentage of the MB where *C. aciphyllum* was present. The abundance ratio (%) of the *C. aciphyllum* in MB was estimated as well. We also quantified the area of incrustations (%) and identified the lichens' species. The measured characteristics of the moss banks of Galindez Island are presented in Table 2 (SI).

Species identification

The species (mosses, liverworts, lichens) composition of the moss banks was determined as follows. Plants were sampled with tweezers from 3–10 plots (1×1 cm) of a moss bank to minimize the disturbance. Samples were sorted, packed and dried, and identified under magnification using a binocular microscope and a microscope using taxonomic keys (Bednarek-Ochyra et al. 2000; Ochyra et al. 2008). All studied samples of Bryophyta from this manuscript were deposited in the bryophyte section of the herbarium at W. Szafer Institute of Botany, Polish Academy of Sciences in Kraków (KRAM). The bryophyte composition of the moss banks of Galindez Island is presented in Table 1(SI). The lichens were identified according to Øvstedal and Smith (2001). The general presence of macromycetes and invertebrates was also recorded.

Reproduction of the experiment provided by Fenton and Smith in 1976

The largest MB on the Galindez Island, Smith moss bank (#26, -65.247672°, -64.250854°), was analyzed by Fenton and Smith in 1976 (Fenton and Smith 1982). Authors studied 33 plots with dimensions 20x20 cm. They documented the species composition, abundance of the living (green) and dead (brown or black) *P. strictum* with others main bryophytes, and quantified the lichen incrustation. We re-evaluated the same parameters. The plots were quite inhomogeneous (Fig. 2), and so we tried to randomly distribute them over the whole territory of a moss bank.

Statistical analysis

Statistical analysis was performed using R Studio 4.0.2 in the package 'vegan', and visualizations were provided in 'ggplot2' package. Shapiro-Wilk test was used to check if continuous variables follow a normal distribution. Spearman correlation coefficient was estimated to evaluate the strength of relations between the moss banks' parameters (area of a moss bank and its mean thickness; area and the total number of species; mean thickness and the number of species etc.). The Wilcoxon rank-sum test ($P = 0.05$) was used to compare moss banks' parameters in the presence or absence of *C. aciphyllum* or minor bryophyte species. We checked whether there is a difference in maximal, minimal or mean thickness of MB, and liverworts' diversity between moss banks where *C. aciphyllum* is present and absent.

Results

Location, parameters and species composition of the moss banks on the Galindez Island

We mapped 44 fragments of Tall moss turf subformation that were interpreted as moss banks on the Galindez Island. All of them tended to grow on the northern slopes (Fig. 1).

The thickness of the moss banks variated from 7 to 75 cm. The mean thickness of the moss banks was 21 cm. The thickness values may evince that solid protected turfs development was initiated after the core species *P. strictum* accumulated ≥ 7 cm of peat.

According to Fig. 3a, thickness and the area of moss banks had a moderate correlation. As it is shown in Fig. 3b, more diverse communities inhabited comparatively small moss banks with an area not more than 800 m^2. Figure 3c illustrates the moderate correlation between the number of Bryophyta species and the mean thickness of the moss bank. Moss banks' areas had a notable variation from 3.4 to 2409.3 m^2, therefore we evaluated also the correlation between the mentioned above parameters for the moss banks that were split into two groups: small (< 250 m^2) and big (> 250 m^2) moss banks. Results are presented in Fig. 1(SI).

According to Table 1, the studied parameters of MB had significant variation. *C. aciphyllum* occurred in 57% of the moss banks. The ratio of *C. aciphyllum'* abundance in the moss bank varied notably (from < 1–43%).

Table 1

Summary of the main characteristic of moss banks of Galindez Island (Argentine Islands, Graham Coast)

Total number of moss banks	**44**
Area, range, m^2	3.4-2409.3
Area, Mean ± Standard Deviation//Sample value, m2	343 ± 487/237603
Thickness, range, cm	7–75
Minimal thickness, Mean ± Standard Deviation/Sample value, cm	13.8 ± 5.8/33.8
Maximal thickness, Mean ± Standard Deviation/Sample value, cm	33.4 ± 11.96/143
Incrustation, range, %	0.5–52.5
Incrustation, Mean ± Standard Deviation/Sample value, %	17 ± 16/244
Abundance ratio of brown and black *Polytrichum strictum*, %	1–90
Abundance ratio of brown and black *Polytrichum strictum*: Mean ± Standard Deviation/Sample value, %	21 ± 20/406
Abundance ratio of green *Polytrichum strictum* range, %	0-96.5
Abundance ratio of green *Polytrichum strictum*: Mean ± Standard Deviation/Sample value, %	62 ± 24/569
Occurrence of *Chorisodontium aciphyllum* in moss banks, %	57
Abundance ratio of *Chorisodontium aciphyllum* in moss bank, %	0–43
Abundance ratio of *Chorisodontium aciphyllum*: Mean ± Standard Deviation/Sample value, %	3.4 ± 8.7/76

Figure 4a-c illustrates the effect of the moss banks' thickness on the presence of *C. aciphyllum.* According to Fig. 4a-c, this species occurred more frequently when the thickness was higher. Figure 4d shows that the availability of *C. aciphyllum* was related to liverworts' diversity: the occurrence of the *C. aciphyllum* was higher in the moss banks with higher liverworts' diversity.

The bryophyte species composition of MB on Galindez Island included 13 moss and three liverworts'. The frequencies of occurrence of all species are given on Fig. 5.

Alongside the core *P. strictum* that had 100% occurrence, *Pohlia nutans* (98%) and core species for Moss carpet subformation *Sanionia georgicouncinata* (Müll. Hal.) Ochyra (88.6%) were highly abundant. *Warnstorfia fontianaliopsis* (Müll.Hal.) Ochyra and *Chorisodontium aciphyllum* had an occurrence of 57%. The occurrence of other mosses in the studied moss banks was less than 50%. *Lophozia* cf. *groenlandica* (Nees) Macoun was the rarest of the found liverwort (43%), unlike two very common species: *Barbilophozia hatcherii* (A. Evans) Loeske (75%) and *Cephaloziella varians* (Gottsche) Steph. (80%).

The vascular plants were presented by the single specimen of Antarctic hairgrass (Parnikoza et al. 2018), while Antarctic pearlwort was not found.

Among the bryophyte species, only four were dependent on the thickness of the moss bank (Fig. 6). The occurrence of *Polytrichastrum alpinum*, *Syntrichia magellanica*, *Warnstorfia fontianaliopsis* and *Barbilophozia hatcherii* was significantly higher in the thicker moss banks.

The Smith moss bank in 1976 and in 2019

As we previously admitted, the analyzed parameters of the studied Smith moss bank varied strongly between the study plots.

Table 2 shows the decrease in the median ratio (%) of the alive green *P. strictum* from 47 to 28%. The maximum ratio was 95% in 1976 and 90% in 2019, and the minimum ratio fell to 1% in 2019. The occurrence of green moss was mostly the same, as it was present in all 33 study plots. The amount of brown and black *P. strictum* increased from 15% recorded by Fenton and Smith (1982) to 59% in 2019. The minimal ratio of brown and black moss rose to 5% in 2019. Besides, dead moss was found in all studied plots in our study. The total coverage of *P. strictum* on the moss bank also grew from 62 to 87%. The amount of *C. aciphyllum* remained stable. The mean ratio of *C. aciphyllum* abundance grew from 2 to 3%, the maximal ratio decreased from 45 to 40%, and occurrence was 26% in 1976 and 24% in 2019. The abundance ratio of *Pohlia nutans* in the study plots grew from 4 to 11% in 2019, the range parameter was unchanged, yet the occurrence also grew significantly from 50–76%.

Table 2
Parameters of the Smith moss bank (Galindes Island, Argentine Islands): comparison of our data (2019) and the data from the article by Fenton and Smith (1982), data from 1976

Species	Mean, 1976	Mean, 2019	Range, 1976	Range, 2019	Presence on the study plots, 1976	Presence on the study plots, 2019
Abundance ratio of living green *Polytrichum strictum*, %	47	28	20–95	1–90	100	100
Abundance ratio of brown or black *Polytrichum strictum*, %	15	59	0–50	5–98	79	100
Abundance ratio of *Polytrichum strictum*, %	62	87	-	-	-	-
Abundance ratio of *Chorisodontium aciphyllum*, %	2	3	0–45	0–40	26	24
Abundance ratio of *Pohlia nutans*, %	4	11	0–50	0–50	50	76
Ratio of incrustation (mainly *Ochrolechia* sp., *Sphaeropsis globosum* and *Cladonia* spp. %	20	13	0–65	0–80	91	76

Discussion

Galindez moss bank characteristics

The Galindez Island is a high island composed of volcanites of the Argentine Islands Formation (Mytrokhyn and Bakhmutov 2019), which is utterly favourable for the moss bank development. In particular, we found there 44 relatively large fragments of Tall moss turf subformation that we classified as moss banks. Besides the large fragments, there were also smaller diffused fragments of this community. Our data provide information on their current condition. Adjacent low islands composed of granitoid hosted only occasional fragments of Tall moss turf subformation. The literature data about Tall moss turf subformation in this region are scarce, unlike the South Orkneys on the North, and is limited to several pieces of research on the individual moss banks and their main parameters dated by the end of the XX century (Smith and Corner 1973; Fenton and Smith 1982).

Extensive thick turf banks of peat are formed when cushion-shaped turfs coalesce (Ochyra et al. 2008). According to Table 1, the thickness of the shallowest moss bank on the Galindez Island was 7 cm. These data show that solid protected turfs, which form moss banks, developed when the turf thickness of core species *P. strictum* reached 7 cm. The maximal thickness of moss banks was 70 cm, which is close to the data (50 cm) reported by Fenton and Smith for Smith moss bank in 1976 (published in 1982).

Characteristics of moss banks from other Antarctic regions are poorly described, which makes a comparison to the moss banks from the Galindez Island complicated. Moss banks located 500 km to the South in the area of the Lazorev Bay of Alexander Island were shallower comparatively to the moss banks from the Galindez Island reaching a depth of 40 cm (Convey et al. 2011). Such a decrease in thickness can be caused by either latitude gradient or micro-climatic effects. Yet, there are moss banks comparable in depth to those from Lazorev Bay within the more northern region of the Argentine Islands. The prevalence of micro-conditions over the latitude gradient is also shown by other studies (Nuzhyna et al. 2021; Prekrasna et al. 2022).

Drainage is a crucial factor for the moss banks' development, as it was noted by Ochyra et al. (2008). Development of thick moss banks (1–2 m) on the well-drained substrate in the maritime Antarctic supports this statement. In contrast, in humid conditions, Tall moss turf subformation is formed by turf mounds not higher than 15 cm that usually coalesce shaping small undulated stands. According to our observations, development of small-area fragments of Tall moss turf subformation on the Galindez Island is dependent not as much on the humidity of the substrate, but on the wind protection of the site. The community's localization on a northern wind-protected slope likely supports the development of significantly thicker moss banks. This pattern was also observed on the Irizar, Uruguay, Corner, Berthelot and other islands located nearby to Galindez Island.

The threshold thickness that can be used to define Tall moss turf subformation as a moss bank is lacking in the literature, so we used the integrity of the vegetation cover as a moss bank criterion. There was a moderate correlation between thickness and species richness in the two groups of moss banks' (with area < 250 m^2, and area > 250 m^2). The correlation between thickness species number was stronger in moss banks with the bigger areas (Fig. 1 SI).

A well-developed bank covers practically the whole available substrate's surface stretching over it as biogenic fabric. Figure 3a shows that the area of the moss bank and its thickness had a moderate correlation. Most of the moss banks on the island had relatively small areas due to the limited sites where vegetation development is possible, and both area and thickness of the moss bank were definitely dependent on surrounding conditions. Bigger moss banks have more heterogeneous surfaces, so flora's diversity may have a more pronounced association with thicker areas of the MB.

The moss banks condition had varying viability that was manifested in different colours of the moss bank fragments: green, several hues of brown and black. Besides the visually brown dead moss, there was also a pink-coloured moss, which transitioned to brown moss. Different colours were mainly inherent to the core species *P. strictum.* According to Waterman et al. (2018), pigmentation can be an adaptation to unfavourable conditions. The pigmentation can vary from year to year depending on the conditions of a particular season or the preceding one. Waterman et al. (2018) compared the red and the green colour morphotypes of three moss species *Ceratodon purpureus* (Hedw.) Brid., *Bryum pseudotriquetrum* (Hedw.) P.Gaertn., B.Mey. & Scherb. and *Schistidium antarctici* (Cardot) L. I. Savicz & Smirnova. They found that red pigments were closely tied to the cell wall providing a long-term protective function in the Antarctic bryophytes. Microscopical analysis showed that the intense red colour of moss was usually connected with the cell wall. For example, all studied leaves of *Ceratodon purpureus*, both red and green, had numerous healthy and green chloroplasts. The red morphs masked the green chloroplasts by the cell wall pigments. The red mosses grew on the exposed area, and the green mosses inhabited the shadowed area. However, both colour morphs had similar overall concentrations of components absorbing the UV irradiation.

Mosses' reaction to harsh conditions such as UV irradiation and lack of humidity in different parts of Antarctica was under focus in a number of studies. Namely, the reaction of such species as *Ceratodon purpureus* (Post 1990), *Grimmia antarctici* Card. (Robinson 2005), *Ceratodon purpureus*, *Bryum pseudotriquetrum* та *Schistidium antarctici* (Dunn and Robinson 2006), *Sanionia uncinata* (Hedw.) Loeske (Pizarro et al. 2019) was analyzed. According to Turnbull et al. (2009), the DNA of cosmopolitan moss species was protected more effectively from UV radiation under insufficient humidity compared to endemic species. The bipolar *P. strictum* and other relatively common mosses can be efficiently protected by pigments from harmful environmental factors like UV irradiation.

The black-coloured moss is a moss that deceased in response to harsh environmental conditions. Desolation of the moss can be caused by burial under perennial snow (Yu et al. 2016). Such buried under snow patch moss bank was found on Died Moss Ravine on the Galindez Island (Parnikoza et al. 2016b; Yevchun et al. 2021b). Figure 1, demonstrates the remnants of moss banks destroyed by the expansion of the gentoo penguins that started in the summer of 2007/2008 on the Galindez Island (Parnikoza et al. 2018). This clearly evidences the vulnerability of the communities to over-eutrophication. A number of moss banks suffered from the influx of organic matter in 2019–2022.

Accordingly to Table 1, the average amount of green *P. strictum* in all moss banks of the Galindez Island exceeded the amount of black moss, which indirectly evidences the vegetation success of the moss in the studied season. It is reasonable to use this parameter in the future to access the dynamics of moss bank vegetation depending on the environmental conditions.

C. aciphyllum is one of the two core species of Tall moss turf subformation. It is mainly distributed in the north of the maritime Antarctic. In the vicinity of our study area, it vegetated on its southernmost distribution area on the Green Island and on the slopes of Mt. De Maria reaching 400 m a.s.l. (Ochyra et al. 2008). It is present in the moss banks of the Galindez Island as minor species. As described by Ochyra et al. (2008), the mixed moss community develops when *P. strictum* colonises *C. aciphyllum* turfs. Meanwhile, the dominance of *P. strictum* provides the moss bank density and capability to withstand erosion due to the firm attachment of the shoots by rhizoids (Fenton and Smith 1982).

In accordance with our observations, *C. aciphyllum* grew preferably in well-protected habitats like wind-sheltered lowest parts or pockets of the moss bank. Figure 4a-c shows that *C. aciphyllum* occurrence rose when the thickness of the moss bank increased. In our opinion, this is defined by the primary development of the large and thick moss banks in the most protected and favourable parts of the island's landscape, which are numerically insignificant. The mean abundance ratio of *C. aciphyllum* on the

Galindez Island was 0–43%, which is consistent with the results of Fenton and Smith (1982). They claimed that *C. aciphyllum* was less common southwards where the conditions worsened due to drop in humidity and increase of winds' speed. We did not find *C. aciphyllum's* monostands or turfs where it dominated on the Galindez Island as it had been described by Smith and Corner (1973), but we observed such monostands on Uruguay Island.

Besides the two core species only rare *Pohlia nutans* and occasional *Sanionia uncinata* were found in moss banks on the South Orkney Islands, Elephant Island and the region from Arthur Harbor to Argentine Islands (Fenton and Smith 1982). We revealed a much higher diversity for all moss banks of the Galindez Island.

P. nutans was described as a common vegetation component of the MB including the region of the Galindez Islands (Smith and Corner 1973; Fenton and Smith 1982), though it has wide ecological amplitude. The abundance ratio of this species was lacking in the data by Ochyra et al. (2008). *P. nutans* occurred in all moss banks on Galindez Island and was a satellite of *P. strictum.* It had a green morphotype, so it will be assigned to the green moss fraction in the remote studies.

Sanionia georgicouncinata and *Warnstorfia fontinaliopsis* can form fairly large insertions in the moss bank in drier and more humid conditions, respectively. They are not assumed as components of Tall moss turf subformation, and their inclusions can be considered as islands in Bryophyte carpet and mat subformation (Ochyra et al. 2008). *Sanionia* spp. also was described as a pioneer of colonization before the moss bank development (Fenton and Smith 1982).

Some bryophyte species were much less distributed, as it was described by Ochyra et al. (2008). *Bartramia patens* Brid., for instance, was found in our study only five times in highly diverse moss banks (9–12 species). Similarly, poorly abundant on the island *Polytrichastrum alpinum* (Hedw.) G.L.Sm. and *Andreaea depressinervis* were found in the most diverse moss banks. This might evidence that tolerant core moss species mediated the conditions for the rare ones. On the other hand, since these species are often found on rock crevices, ledges, and rocks, their presence may indicate the rock ridges and brows under the moss banks. Moss's colonization of the relief structures develops more diverse niches suitable for the growth of various species. The moderate correlation between species diversity and the moss bank area (Fig. 3b) supports this idea. For example, moss bank #4 (Cemetery Ridge) with an area of 120.5 m^2 was inhabited by 14 Bryophyta species similar to moss bank #2 (Karpaty Ridge) which occupied 1031.7 m^2. Meanwhile, moss bank #1 (Neck ridge) with an area of 2409.3 m^2 was inhabited by 7 moss species and 1 liverwort *Cephaloziella varians.*

We checked the assumption of whether the bryophytes' diversity depends on the moss bank area (Fig. 3b). There were at least a few modest-size moss banks that had rather high species diversity. Favourable micro-conditions and greater thickness, but not the area of the moss bank, were likely ultimate conditions for the elevated species diversity (Fig. 3c).

According to Fig. 6, *Polytrichastrum alpinum*, *Syntrichia magellanica*, *Warnstorfia fontianaliopsis* and *Barbilophozia hatcherii* occurred more frequently when the mean thickness of the moss bank was higher. For this reason, exactly these species can be used as indicators of moss bank thickness. Generally, the distribution of mosses and lichens was limited by the presence of available water and the individual relations of species in the community (Kanda and Inoue 1994).

Fenton and Smith (1982) listed only two liverwort species inhabiting moss banks in the maritime Antarctic: *Barbilophozia hatcherii* and *Cephaloziella varians*. These two species play a significant role in the studied moss banks on the Galindez Island.

Lophozia cf. groenlandica is rare species in the maritime Antarctic, hence its frequent occurrence in Argentine Islands - Kyiv Peninsula region was surprising. Additionally, this species is often associated with moss banks. *L. cf. groenlandica* was registered in moss banks of the Galindez Island (1965, 1975) and the MB edge on Green Island (1981) (Bednarek-Ochyra et al. 2000; KRAM herbarium).

According to Bednarek-Ochyra et al. (2000), antarctic liverworts inhabit more protected sites. Our data provides that *C. aciphyllum* co-occurred with 2–3 liverwort species in most of the banks (except four). Figure 4d supports the co-occurrence of *C. aciphyllum* with at least two liverwort species. The data may indicate that both *C. aciphyllum* and the liverworts are indicators of the most favourable and protected conditions for moss bank development. *C. aciphyllum* can also be used as an indicator for species requiring similar environmental conditions and landscape unevenness under the moss banks. Notably, liverworts on the Galindez Island are well-seen in moss banks pockets where they can create separate small tufts. We noticed that mostly *C. aciphyllum* grew interspersed with *Barbilophozia hatcherii.* Considering the above, *C. aciphyllum* abundance ratio and liverwort species abundance can be recommended as indicators of environmental changes.

Vascular plants were not common in Tall moss turf subformation on the Galindez Island and the overall Argentine Islands - Kyiv Peninsula region. The species can be connected with other plant communities like Bryophyte cushions and mat subformation impregnated in the moss bank. Antarctic hairgrass community preceded the moss bank formation on Rasmussen Point (Loisel et al. 2017).

According to Table 1, there was a big difference in the level of lichen incrustation of different moss banks (0.5–52.5%, with an average of 10%). The data is consistent with the data by Fenton and Smith (1982), who described that species diversity and the percentage of incrustation decreased in more southerly parts of maritime Antarctic. We can assume that incrustation did not develop on all bryophyte species and was mostly dependent on the *P. strictum's* growth. Otherwise, the moss bank provided more heterogeneous micro-conditions suitable for higher species diversity while evolving.

Fenton and Smith (1982) described the following lichen species that form incrustations over *P. strictum* moss banks in South Georgia: *Cetraria islandica* (L.) Ach., *Sphaerophorus globosus* (Huds.) Vain. and *Stereocaulon alpinum* Laurer ex Funck. *Usnea antarctica* Du Rietz., *Alectoria* spp., and *Cornicularia* spp. form incustation in rarer cases (Bjorck et al. 1991). The living surface of the banks is often partly covered by lichens, notably species of *Alectoria*, *Bryoria*, *Cladonia*, *Sphaerophorus*, *Usnea*, and several crustose genera (Fenton and Smith, 1982)

In occasional years, we also recorded macromycetes of likely *Omphalina* genus on the moss bank #23 on the Govorukha Dome. The preliminary results of our study show that moss banks had much fewer invertebrate taxa compared to fragments of the moss carpet or mat subformations. On the contrary, Fenton and Smith (1982) admitted the presence of Nematoda, Collembola and Acari within the moss bank communities, so the question requires additional study.

Smith Moss Bank Analysis

To assess the moss banks' reflection to the environmental changes, we compared the parameters of the Smith moss bank located the Galindez Island to the data obtained for this moss bank in 1976 by Fenton and Smith (1982). In particular, we compared the permafrost depth, ratio abundance of moss colour morphotypes and species composition.

The Smith moss bank (# 26 on Fig. 1) has a west orientation, irregular landscape and rises 4–11 m over Stella Creek. According to Fenton and Smith (1982), the average permafrost depth of this moss bank was 23 cm in 1976, yet in 2019 permafrost laid much deeper at the depth of 35.5 cm.

While comparing the ratio of brown, black moss, alive green moss and the total ratio of *P. strictum* (Table 2), the increase in the amount of brown and black moss during the last 46 years becomes obvious. Its occurrence in the study plots increased as well. In our study, it occurred in all plots amounting to at least 5%. The total amount of *P. strictum* on the plots elevated compared to the data by Fenton and Smith (1982), which was the result of the increase of black moss quantity. Progressive deterioration of the summer season conditions that caused decease of moss turf can be a reason for a such an increase in black moss quantity. It is worth noting, that according to our observations, *P. strictum* is nitrophobic, so it can suffer from the organic input provided by birds, nesting skua in particular (Ivanets et al. 2022). In any case, the proportion of the colour morphotypes of the dominant *P. strictum* comes across as an appropriate parameter for monitoring of environmental parameters.

According to Table 2, the ratio and occurrence of *C. aciphyllum* remained stable. *C. aciphyllum* was mostly found in depressions or in the lowest parts of the moss banks, where the rigid shoots of *P. strictum* protected it from the wind (Fig. 2c). As we indicated above, liverworts tend to colonize the most protected parts of moss banks as well. Thus, it confirms that *C. aciphyllum* is the indicator of the most protected and likely most stable conditions on the moss bank.

Occurrence of *P. nutans* (Table 2) shows that it did not exceed half of the plot area, and its relative amount somewhat increased compared to the previous data. This indicates that the species had the ecological niche of a hardy satellite of *P. strictum*, which is illustrated by Fig. 2. The maximum amount of *P. nutans* on the plots did not change and did not exceed 50%. Various researchers (Fenton and Smith 1982; Ochyra et al. 2008; Yu et al. 2016) considered that *P. nutans* developed in conditions with increased humidity. That is why changes in its amount may be an ecological signal.

Interestingly, the mean incrustation ratio decreased from 20% in 1976 to 13% in 2019. The maximum incrustation ratio rose to 80%, and occurrence decreased from 91 to 76 (Table 2). Given that the incrustation includes also slow growing fruticose lichens, Cladonia spp. and Sphaerophorus globosus, one could assume that the incrustation should grow with moss bank development. However, the black P. strictum's increase and incrustation's decrease may reflect a number of unfavourable environmental events that happened to the moss bank over a timespan (Fig. 6d). According to our observations, lichens colonized green moss more often that the black one, which requires more detailed research. It is notable that incrustation was revealed to be dynamic.

The study of Kanda and Inoue (1994) showed that lichens' primary thalli developed on the exposed surfaces of moss tufts free from sand and influenced further moss vegetation. We may assume that incrustation developed not on all bryophyte species, but mostly on P. strictum. Fenton and Smith (1982) described incrustation by the Lecidea sp. and cyanophytes, which were not observed in our study at all. Kanda and Inoue (1994) found that *Nostoc* sp. and *Phormidium* sp. developed on more humid sites of moss tufts. No macroalgae, except for *Prasiola crispa* in places affected by birds and nesting sites, were found on the Smith moss bank. The absence of macroalgae in 2019 might evidence the changing environment. The above-mentioned genera of colonial algae were not found on other moss banks of Galindez Island. A more detailed study of the colonial algae is needed to assess the issue fully.

The observed changes in this moss bank are consistent with other scientists' observations of different moss communities. Robinson et al. (2018) established a number of monitoring plots on two sites on two peninsulas of the Windmill Island, West Antarctica, and tracked them for 13 years. They found that the species composition of bryophyte carpet vegetation changed rapidly following environmental change. The changes in moss community morphotypes (green vs. brown moss and species composition) correlated with micro-conditions of humidity following landscape depressions on both sites as well as on the study plots. The authors think that despite the low growth rates, the Antarctic mosses reflect the environmental changes by the tissue characteristics and they are rapidly reacting markers of environmental change.

Yu et al. (2016) analyzed the carbon C14 isotopes in their samples and found a correlation between the temperature and growth rates, and changes in the species composition of Antarctic terrestrial communities. It was also shown that the recent warming recorded in the region during the melting of glaciers and permafrost caused the rejuvenation of moss banks: carbon fixation in moss cells grew significantly (Yu et al. 2016).

To sum up, we were able to record changes in the Smith moss bank's parameters. The approach may be used as a basis for regular monitoring, yet some parameters should be measured using more advanced techniques. Special attention should be paid to the dynamics of various morphotypes of the dominant mosses, and to moss bank incrustation. Such monitoring is necessary not only for the moss banks but for *C. aciphyllum*, which is on the edge of its distribution range in the region of the Argentine Islands – Kyiv Peninsula, endangered and requires attention and conservation.

Conclusion

Diversity of Tall moss turf subformation on Galindez Island was studied. Galindez moss banks' bryophyte flora included 13 species of mosses and three species of liverworts. Some expansion of the list of species included in the moss banks of the island is not related to their development, but to more thorough research. The higher richness of the moss banks’ flora detected in the study was not connected to the development of the moss banks, but to more detailed study. There was no correlation between the species richness and the area of the moss bank, but the species richness positively correlated with the moss bank depth. We supposed species diversity of moss bank depended presumably on the age of moss bank and micro-conditions rather than on area. Abundance of some moss species correlated with moss bank depth. Additionally, *Chorisodontium aciphyllum* and the liverworts were considered indicators of the most favourable and protected conditions for moss bank development. The Smith moss bank, which is the largest and deepest moss bank of Galidez Island, was analyzed similarly to the parameters measured there in 1976 (Fenton and Smith 1982). A comparison of our results and results by Fenton and Smith (1982) revealed an increase in the amount of brown- and black-coloured morphotypes of *Polytrichum strictum* cushions, no significant changes in the ratio of *Chorisodontium aciphyllum* and a decrease in the lichen incrustation. These results show that the ratio of *Polytrichum strictum’s* coloured morphotypes, *Chorisodontium aciphyllum* and liverworts’ abundance are informative parameters for long-term monitoring of moss bank in response to external environmental factors. Ratio of the colour morhotypes of *Polytrichum strictum* are encouraging in particular, because this parameter can be studied remotely with the means of unmanned aerial vehicles.

Declarations

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Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All applicable international, national and/or institutional guidelines for the care and use of animals were followed.

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Figures

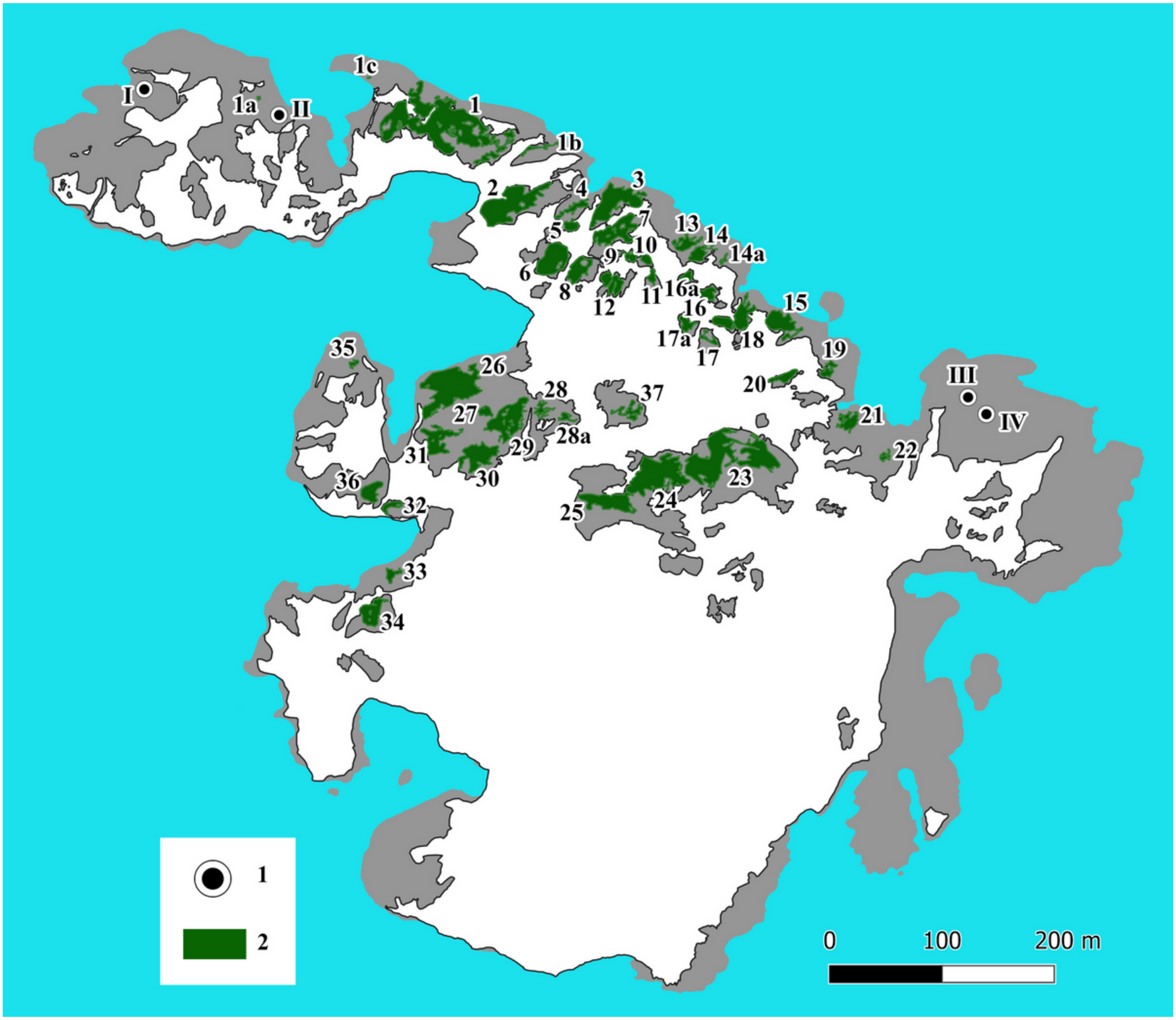

Figure 1

The map of the moss banks on the Galindez Island, Argentine Islands, Graham Coast: 1 - moss banks destroyed by the expansion of the gentoo penguins after 2007, 2 – alive moss banks

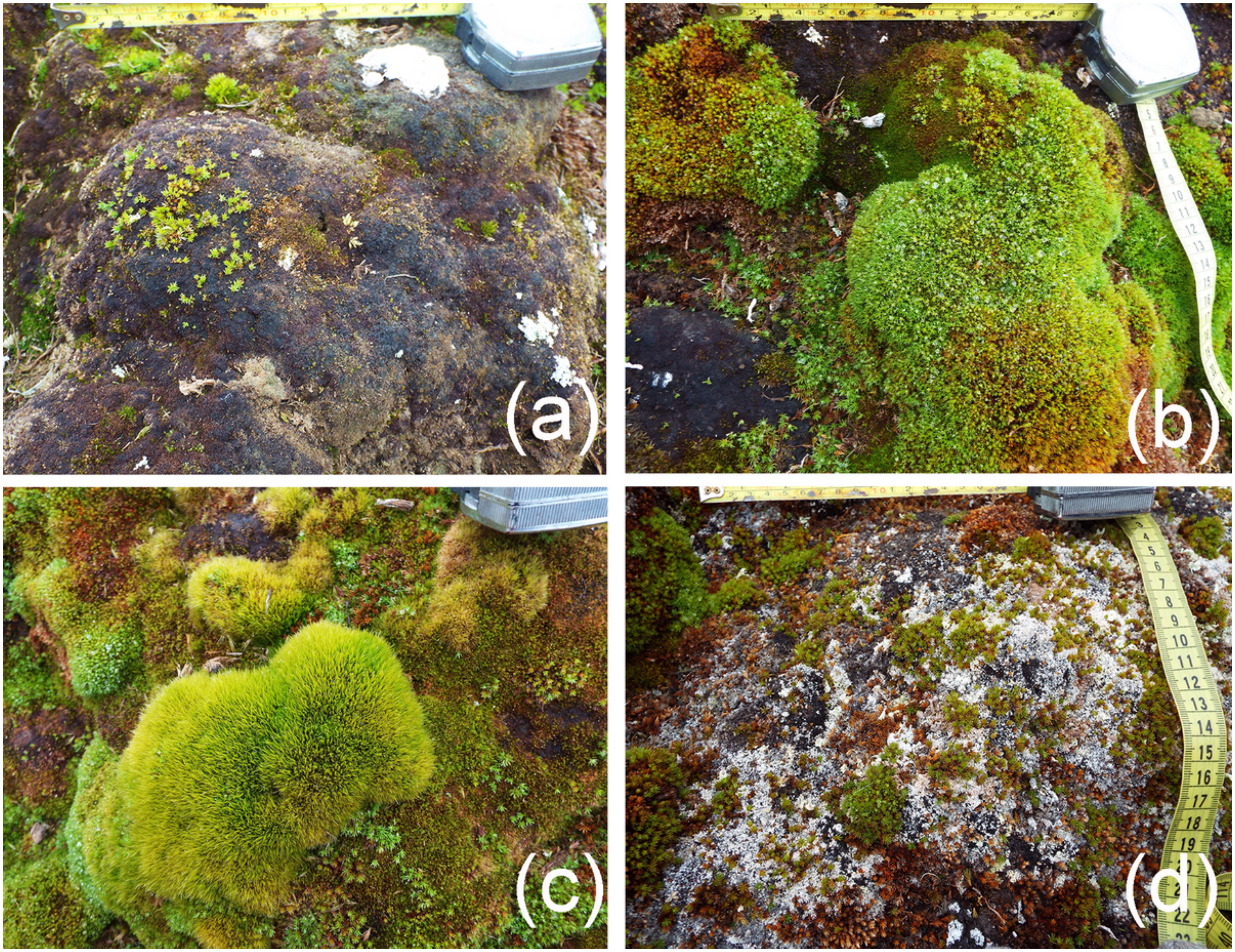

Figure 2

Variability of the study plots of the Smith moss bank, Galindez Island, Argentine Islands, Graham Coast in 2018/2019

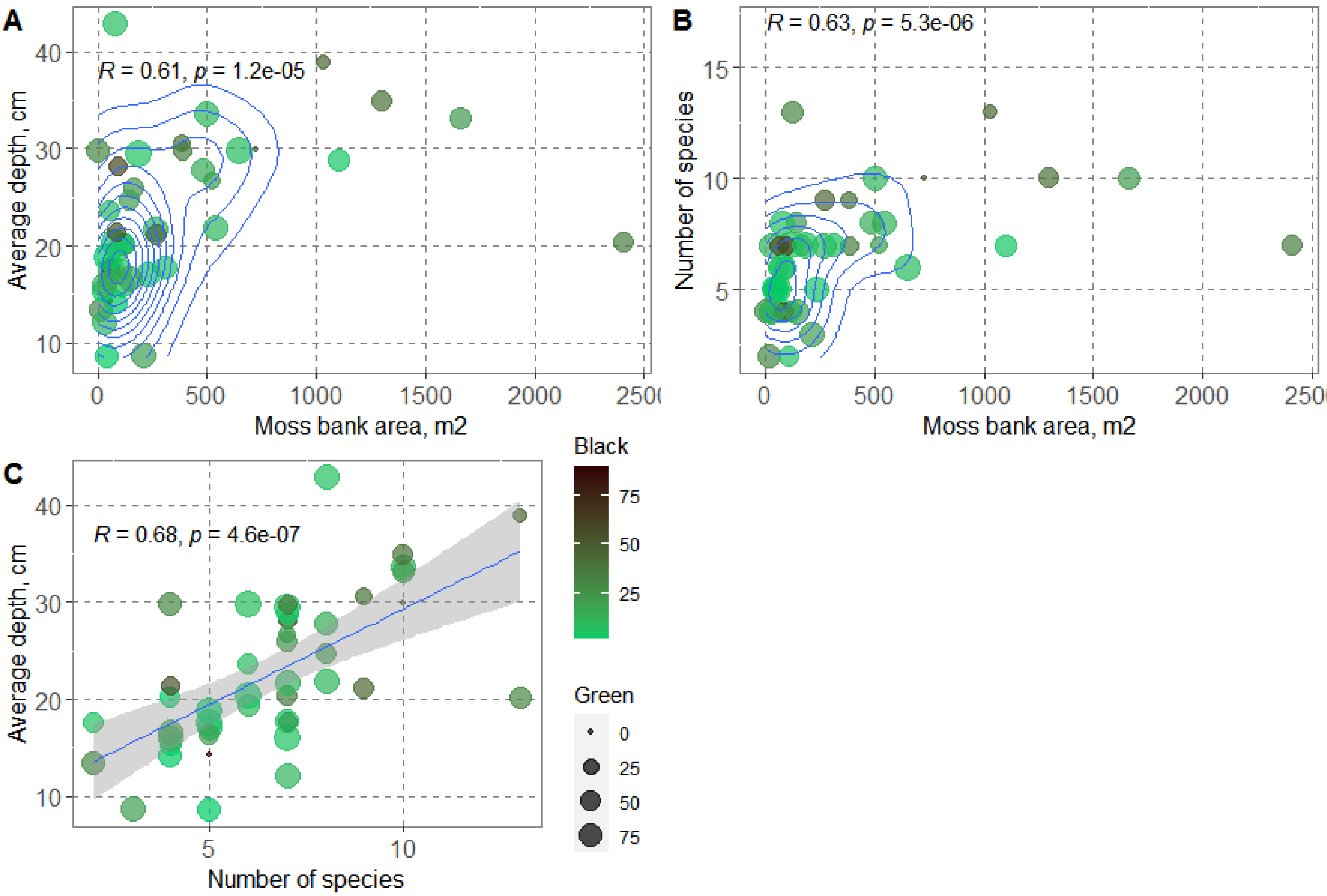

Figure 3

The dependence of the mean thickness on the moss bank's area (**a**), dependence of the total species richness of Bryophytes on the moss bank's area (**b**), dependence of the on the moss bank's area on the total species richness of Bryophytes (**c**) for Galindez Island, Argentine Islands, Graham Coast

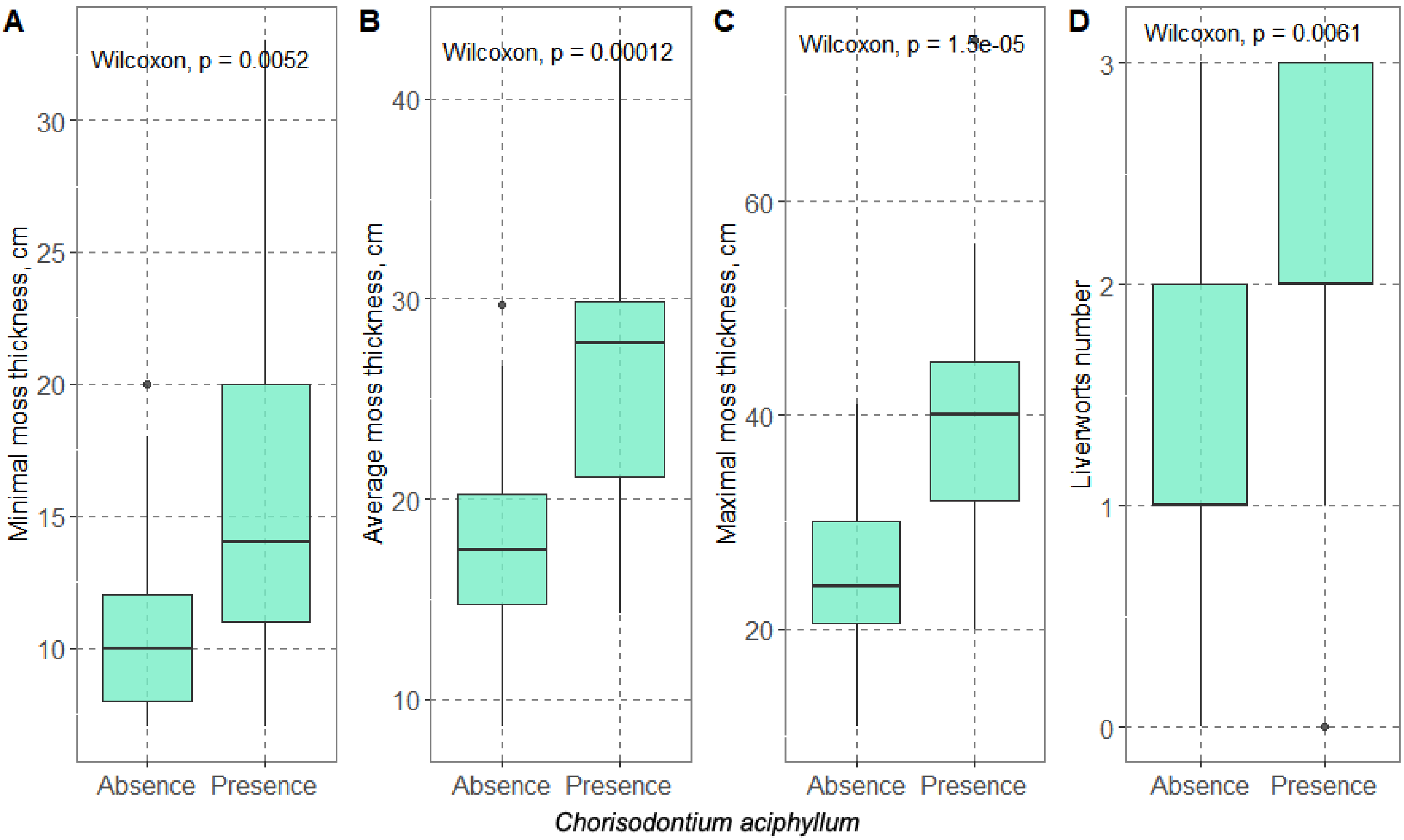

Figure 4

The dependence of the presence/absence of *Chorisodontium aciphyllum* on the moss banks of the Galindez Island, Argentine Islands, Graham Coast on (**a**) maximum, (**b**) minimum, (**c**) mean thickness of moss banks on the Galindez Island, (**d**) the dependence of the presence of *Chorisodontium aciphyllum*on the total number of liverworts

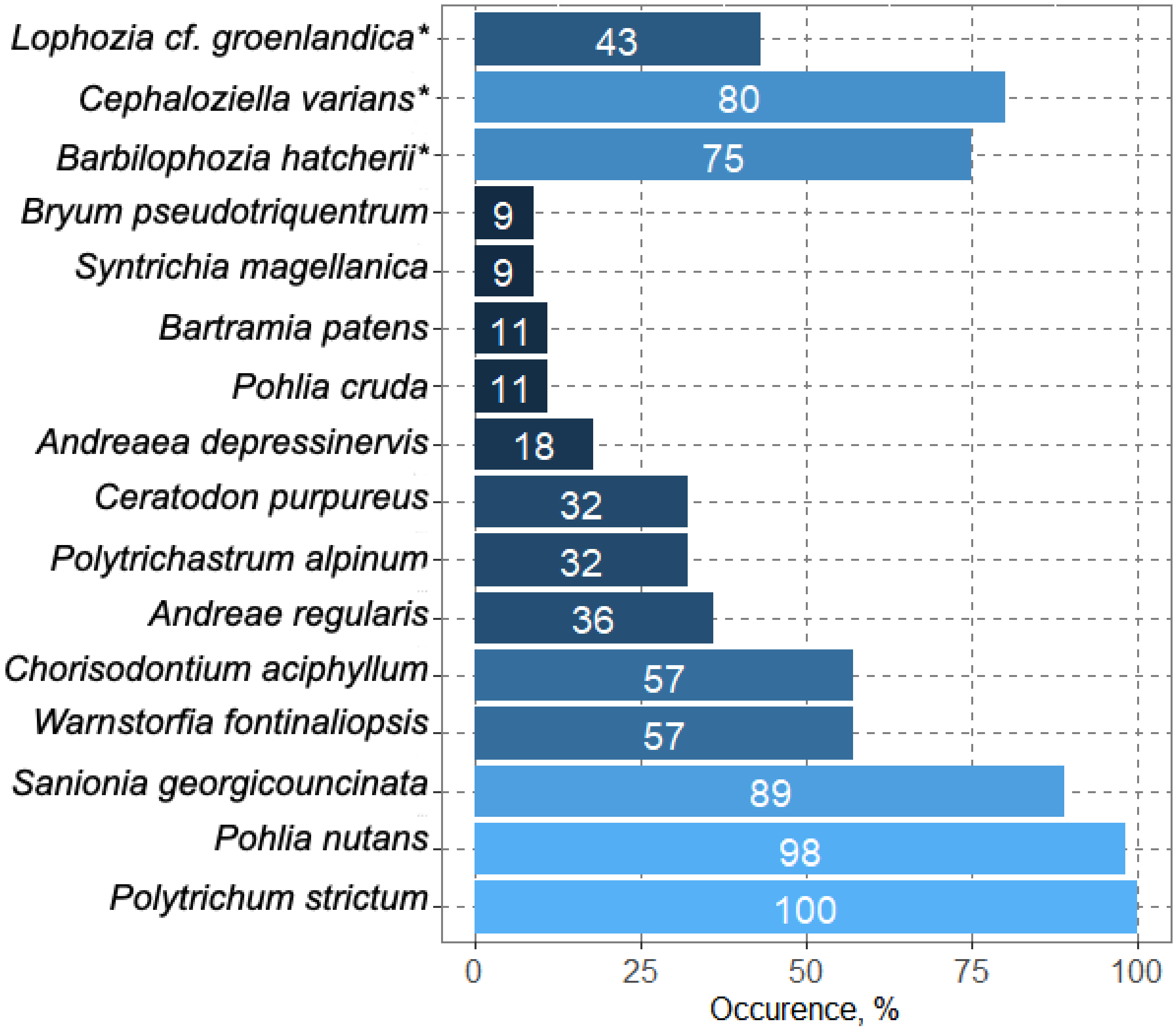

Figure 5

Occurrence frequencies of the mosses and liverworts (indicated by *) species from the moss banks on the Galindez Island, Argentine Islands, Graham Coast

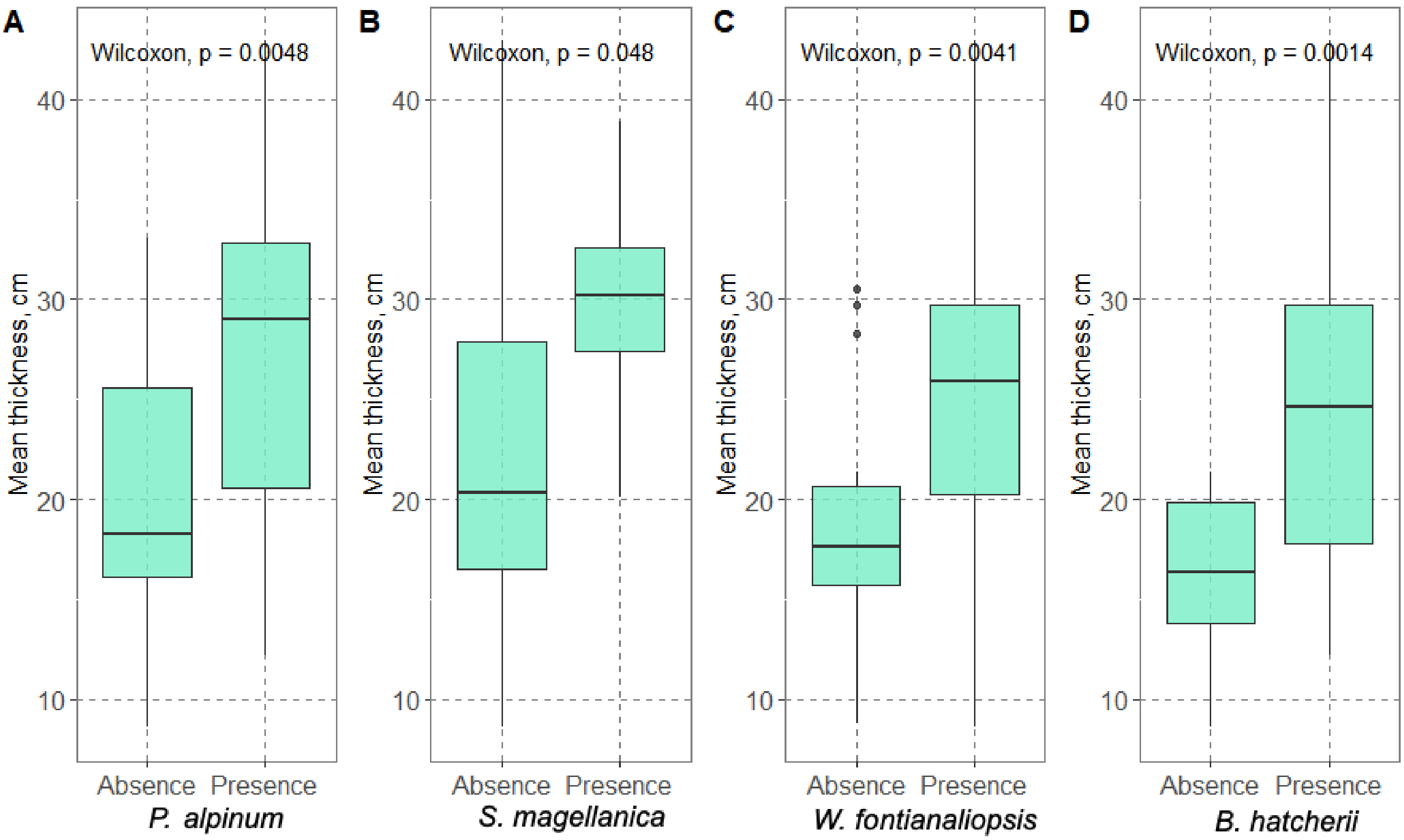

Figure 6

The dependence of the presence of four moss species: *Polytrichastrum alpinum* (**a**), *Syntrichia magellanica* (**b**), *Warnstorfia fontianaliopsis* (**c**), *Barbilophozia hatcherii* (**d**) on the moss banks' mean thickness on the Galindez Island, Argentine Islands, Graham Coast

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