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STRUCTURE AND SPATIAL DISTRIBUTION OF VEGETATION IN MARITIME ANTARCTICA: A CASE STUDY OF A PROTECTED AREA IN HARMONY POINT, NELSON ISLAND

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ABSTRACT

Harmony Point, located on Nelson Island in the South Shetland Islands, is one of the most ecologically significant Antarctic Specially Protected Areas (ASPA No. 133). Despite its recognized importance, the plant diversity and vegetation patterns of the region remain insufficiently documented. This study provides a detailed floristic and phytosociological survey and maps the spatial distribution of terrestrial plant communities across six sectors, including four beaches and two plateaus. Fieldwork was conducted during the austral summer of 2019 using standardized quadrat sampling and drone-based aerial imaging. A total of 75 species were identified, including one flowering plant (*Deschampsia antarctica*), 30 bryophytes (27 mosses and 3 liverworts), 42 lichens, and 2 terrestrial algae (*Prasiola* spp.). Seven distinct plant communities were recognized, shaped by environmental gradients, faunal influence (e.g., penguin and petrel colonies, fur and Weddell seals), and substrate availability. A novel zoned sociation involving *Usnea aurantiacoatra*, *Himantormia lugubris*, and *Ochrolechia frigida* is described here for the first time in Antarctica. Our results highlight the ecological relevance and floristic uniqueness of Harmony Point and reinforce the need for continued monitoring and conservation strategies in light of increasing climate change and human activity in the region.

Keywords: Phytosociology; Mapping; Plant distribution; Formations.

RESUMO

ESTRUTURA E DISTRIBUIÇÃO ESPACIAL DA VEGETAÇÃO NA ANTÁRTICA MARÍTIMA: UM ESTUDO DE CASO DE UMA ÁREA ESPECIALMENTE PROTEGIDA EM HARMONY POINT, ILHA NELSON.

Harmony Point, localizada na Ilha Nelson, no arquipélago das Ilhas Shetland do Sul, é uma das Áreas Antárticas Especialmente Protegidas (ASPA nº 133) de grande importância ecológica. Apesar de sua reconhecida relevância, a diversidade vegetal e os padrões da vegetação da região ainda não estão suficientemente documentados. Este estudo apresenta um levantamento florístico e fitossociológico detalhado e mapeia a distribuição espacial das comunidades vegetais em seis setores, incluindo quatro praias e dois platôs. O trabalho de campo foi realizado durante o verão austral de 2019, utilizando amostragem padronizada por quadrados e imagens aéreas obtidas por drones. Um total de 75 espécies foram identificadas, incluindo uma angiosperma (*Deschampsia antarctica*), 30 briófitas (27 musgos e 3 hepáticas), 42 líquens e 2 algas terrestres (*Prasiola* spp.). Sete comunidades vegetais distintas foram reconhecidas, moldadas por gradientes ambientais, influência da fauna (por exemplo, colônias de pinguins e petréis, lobos-marinhos e focas-de-Weddell) e disponibilidade de substrato. Uma nova associação zonal envolvendo *Usnea aurantiacoatra*, *Himantormia lugubris* e *Ochrolechia frigida* é descrita aqui pela primeira vez na Antártica. Nossos resultados destacam a relevância ecológica e a singularidade florística de Harmony Point e reforçam a necessidade de monitoramento contínuo e estratégias de conservação em vista do aumento das mudanças climáticas e da atividade humana na região.

Palavras-chave: Fitossociologia; Mapeamento; Distribuição vegetal; Formações vegetais.

RESUMEN

ESTRUCTURA Y DISTRIBUCIÓN ESPACIAL DE LA VEGETACIÓN EN LA ANTÁRTIDA MARÍTIMA: UN ESTUDIO DE CASO DE UN ÁREA PROTEGIDA EN PUNTA HARMONY, ISLA NELSON. Punta Harmony, ubicada en la isla Nelson, en las islas Shetland del Sur, es una de las Áreas Antárticas Especialmente Protegidas (ASPA n.º 133) de mayor importancia ecológica. A pesar de su reconocida relevancia, la diversidad vegetal y los patrones de vegetación de la región aún no han sido documentados suficientemente. Este estudio presenta un análisis florístico y fitosociológico detallado y cartografía la distribución espacial de las comunidades de plantas terrestres en seis sectores, que incluyen cuatro playas y dos mesetas. El trabajo de campo se llevó a cabo durante el verano austral de 2019 mediante muestreo estandarizado por cuadrantes e imágenes aéreas obtenidas con drones. Se identificaron un total de 75 especies, entre ellas una angiosperma (*Deschampsia antarctica*), 30 briófitas (27 musgos y 3 hepáticas), 42 líquenes y 2 algas terrestres (*Prasiola* spp.). Se reconocieron siete comunidades vegetales distintas, modeladas por gradientes ambientales, la influencia de la fauna (por ejemplo, colonias de pingüinos y petreles, lobos marinos y focas de Weddell) y la disponibilidad de sustrato. Aquí se describe por primera vez en la Antártida una nueva asociación zonificada que involucra a *Usnea aurantiacoatra*, *Himantormia lugubris* y *Ochrolechia frigida*. Nuestros resultados destacan la relevancia ecológica y la singularidad florística de Harmony Point, y refuerzan la necesidad de mantener estrategias de monitoreo y conservación ante el aumento del cambio climático y de la actividad humana en la región.

Palabras clave: Fitosociología; Cartografía; Distribución de plantas; Formaciones de plantas.

1 INTRODUCTION

Antarctica is the most remote and coldest continent on Earth, and global climate change is affecting both its marine and terrestrial ecosystems (Colesie et al., 2022; Convey & Peck, 2019). Between 1951 and 2000, the Antarctic Peninsula experienced a marked warming, with an average increase of 0.56 °C per decade (equivalent to 0.056 °C per year), leading to significant changes in vegetation extent and cover (Turner et al., 2020). The pronounced warming in the western sector of the peninsula and the Scotia Arc has resulted in increased precipitation, changes in wind patterns, and a longer melt season (Amesbury et al., 2017; Clements, 2021). Rapid glacier retreat has exposed new substrates, expanded ice-free areas, and favored plant colonization (Cannone et al., 2022; Cook et al., 2005; Robinson et al., 2018).

Environmental conditions in Antarctica are generally extreme, with temperatures well below freezing during winter, pronounced seasonality in light availability, frequent desiccation, and exposure to abrasion from strong winds. In Maritime Antarctica, particularly in the South Shetland Islands, conditions are comparatively less severe than on the continental mainland, allowing the development of extensive plant communities. In addition to the two native flowering plant species, the Poaceae *Deschampsia antarctica* Desv. and the Caryophyllaceae *Colobanthus quitensis* (Kunth) Bartl., lichens and bryophytes, especially mosses, are the dominant plant groups in Antarctica and are thus the primary colonizers of recently deglaciated polar soils (Favero-Longo et al., 2012; Olech & Słaby, 2016). Bryophytes are divided into two major taxonomic groups: liverworts, with 27 known species (Bednarek-Ochyra et al., 2000), and mosses, with 111 species described (Ochyra et al., 2008). Regarding lichenized fungi, Øvstedal and Lewis-Smith (2001) reported 386 species, although this number may reach approximately 500 (Øvstedal & Schaefer, 2013). Adapted to extreme conditions, these organisms are mainly found in coastal areas, islands, rocky slopes, or nunataks, colonizing soil and exposed rocks (Bokhorst et al., 2007; Robinson et al., 2003). Their growth is slow, constrained by the short photoperiod and limited availability of liquid water (Poelking et al., 2015). Plant communities show an irregular spatial distribution in response to multiple environmental conditions and gradients (Ferrari et al., 2021; Matos et al., 2024; Schmitz et al., 2020).

In recently deglaciated areas of Maritime Antarctica, seabirds play a key role in soil modification, primarily through nutrient input via guano at nesting sites. This process enhances chemical weathering, promotes the formation of ornithogenic soils, and creates favorable conditions for plant establishment (Bockheim, 2015; Simas et al., 2007; Tatur & Myrcha, 1993). The distribution and development of plant species are strongly influenced by abiotic factors such as soil chemical and physical properties, topography, substrate type, and nutrient availability, as well as by interactions with local fauna (Campbell & Claridge, 1987; Ferrari et al., 2021; Lewis-Smith, 2005; Robinson et al., 2018; Schmitz et al., 2020).

Recent studies have shown that climate change is already impacting ancient moss banks in East Antarctica (Robinson et al., 2018). Mosses absorb water through aboveground tissues and are therefore likely to be more responsive than vascular plants to changes in climate and precipitation chemistry (Bobbink et al., 2010). Lichens, although generally more abundant across Antarctica, grow extremely slowly and may respond differently to environmental changes (Robinson et al., 2018). More broadly, shifts in the composition and abundance of cryptogamic communities have been linked to climate change, the introduction of non-native species, and other anthropogenic pressures (Bokhorst et al., 2007; Hughes & Convey, 2023). In this context, remote sensing techniques using aerial and satellite imagery have revealed structural changes in vegetation communities across various regions (Duffy & Lee, 2019; King et al., 2020; Lee et al., 2017; Robinson et al., 2018).

Nelson Island is one of the main islands in the South Shetland Archipelago, and Harmony Point is among the most important ice-free areas in Maritime Antarctica. This is largely because Harmony Point comprises an Antarctic Specially Protected Area (ASPA No. 133, Antarctic Treaty Consultative Meeting [ATCM], 2005), which hosts breeding colonies of at least 12 bird species and supports abundant, yet still understudied, vegetation. This vegetation develops on various soil types and is particularly characterized by extensive moss carpets, together with diverse lichens and fungi (Antarctic Treaty Consultative Meeting [ATCM], 2022; Ochyra et al., 2008).

Recent studies have described the soils, landscapes, and pedogenetic processes occurring at Harmony Point, as well as their relationships with vegetation (Rodrigues et al., 2019; Sacramento

et al., 2023). However, these studies provided only brief descriptions of the vegetation, without presenting a comprehensive species inventory for the area. According to Rodrigues et al. (2019), on the southern plateau, vegetation in higher areas is primarily composed of nitrophobic species that are highly resistant to wind exposure and desiccation. The dominant formation is a dense mat of the muscicolous lichen *Himantormia lugubris*, closely associated with the mosses *Andreaea gainii* and *A. depressinervis*, though it also occasionally occurs with other carpet-forming mosses. Other muscicolous lichens are also common, particularly *Ochrolechia frigida*, *Psoroma hypnorum*, and *Cladonia* spp. In some areas, *Andreaea* spp. form lichen-free patches, developing into dark brown to black cushions that cover exposed rock surfaces as primary colonizers. *Usnea aurantiaco-atra* is found sterile on low hills above the plateaus, associated with mosses and other lichens on rocky outcrops.

On the northern plateau, Sacramento et al. (2023) classified the vegetation into four classes, which together occupy 13.3% of the area: moss carpet subformation (7%), lichen, carpet and short moss turf (5%), macroalgae and cyanobacteria (less than 1%), and lichen (less than 1%).

Despite previous studies, a clear need remains for a comprehensive survey of the taxonomic composition and spatial distribution of vegetation at Harmony Point. This Antarctic Specially Protected Area (ASPA) is of high ecological importance, and detailed knowledge of its terrestrial plant communities is essential to inform and strengthen conservation strategies. Therefore, this study aimed to characterize the structure and map the spatial distribution of terrestrial vegetation communities at Harmony Point, Nelson Island, Maritime Antarctica, contributing to the understanding of its ecological patterns and supporting future research and conservation efforts.

2 MATERIAL AND METHODS

This work was carried out over 35 days during the 2019 austral summer (January–February) at Harmony Point, Nelson Island (62°18′ S, 59°10′ W; Figure 1), in areas adjacent to the Argentine Refuge Gurruchaga. The plant composition was listed through field surveys, where samples were collected

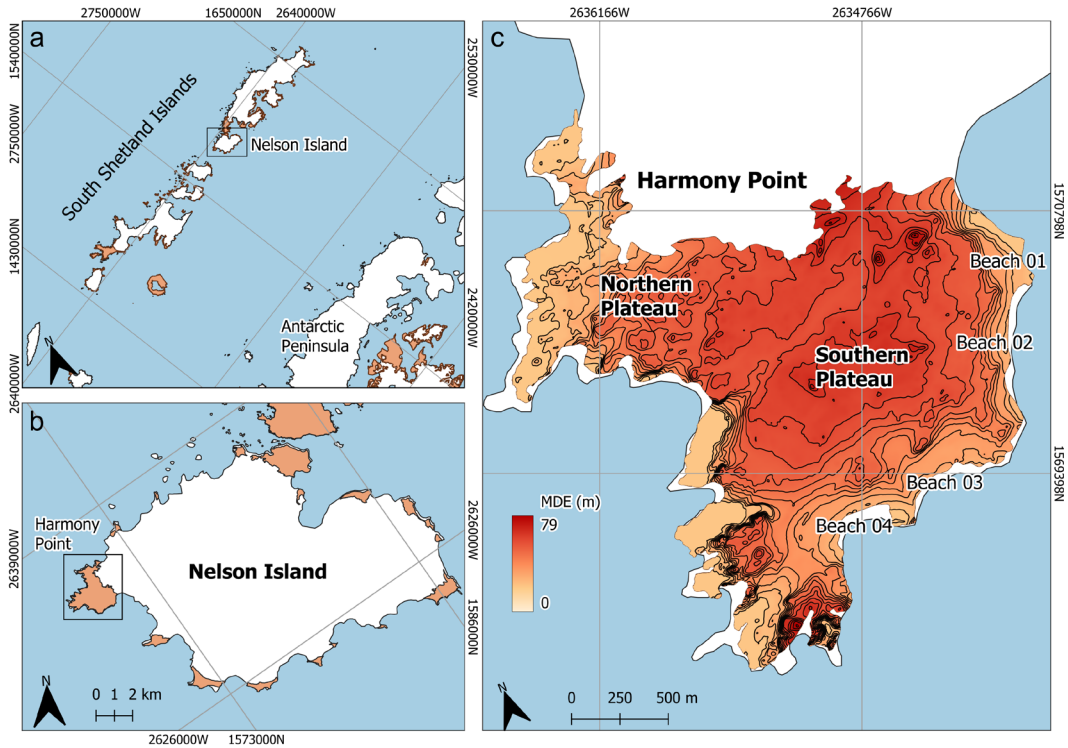

FIGURE 1 – Location of the study area: (a) South Shetland Islands archipelago; (b) Nelson Island; (c) topography of Harmony Point (ASPA 133) showing the sites mentioned in the text.

and dried to become part of the Herbarium HBEI collection at the Universidade Federal do Pampa (UNIPAMPA), Brazil. Moss species were identified using the taxonomic keys of Putzke and Pereira (2001), Ochyra (1998), and Ochyra et al. (2008), whereas lichen species were identified using the keys of Redón (1985), Øvstedal and Lewis-Smith (2001), and Olech (2004). The phytosociological survey was conducted using 20 × 20 cm quadrats placed within each plant formation, spaced at 2 m intervals along lines set 2 m apart, to determine the dominant species in each formation. Plant formations were classified following Lindsay (1971).

An aerial survey of the study area was conducted using a DJI Phantom 4 remotely piloted aircraft (RPA), with images captured at a flight altitude of 70 m under stable weather conditions in February 2019. The images were georeferenced using ground control points recorded with a GNSS receiver and processed in Agisoft which generated an orthomosaic. The mapping was performed at a working scale of 1:500, allowing detailed delineation of vegetation patches.

The area was divided into six sectors (four southern beaches and two plateaus) to better interpret spatial patterns of vegetation distribution (Figure 2). Vegetation formations were manually classified into distinct structural types (e.g., moss carpets, lichen-dominated crusts, mixed moss–lichen communities, and guano-enriched nitrophilous assemblages) based on the communities and associations observed during fieldwork. The class boundaries and composition were verified through ground-truthing during the field campaign. Each formation was manually delineated and hand-colored in the final map to ensure precision in its spatial extent. The Cob-Cal software was used to quantify the coverage of each vegetation formation. The sectors are discussed individually; for example, the north-western beaches are generally dominated by penguin colonies, which create a specific nitrophilous vegetation association.

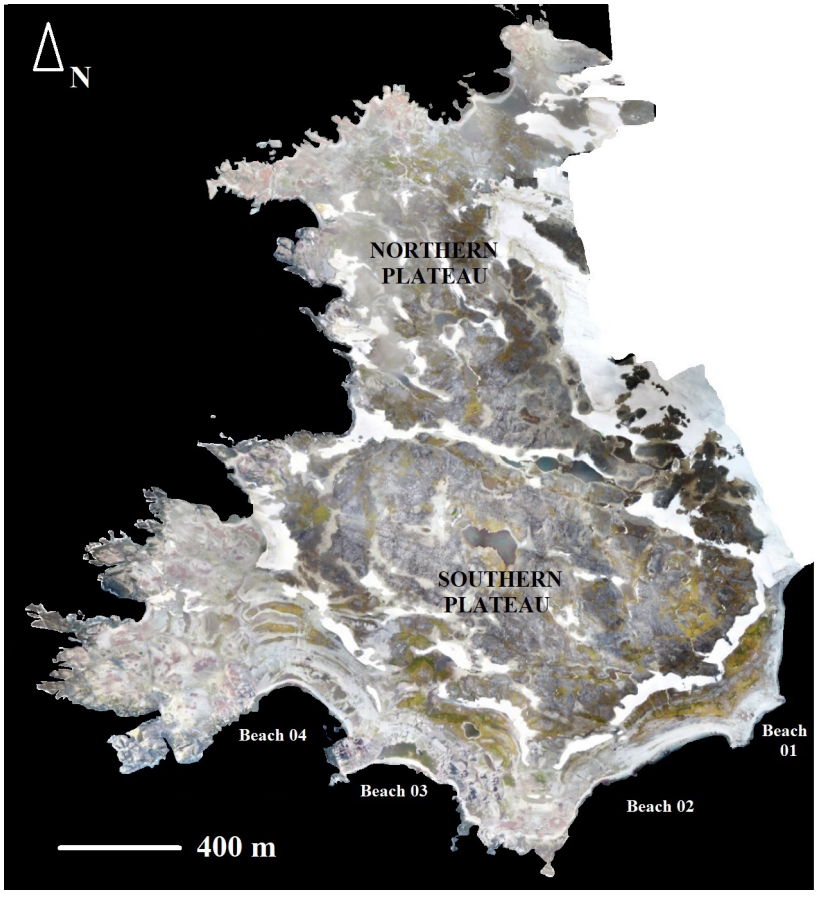

FIGURE 2 – Harmony Point is divided into two plateaus: Northern and Southern. The Southern plateau is further subdivided into four sectors: Beaches 1, 2, 3, and 4, where phytosociological surveys were conducted.

3 RESULTS AND DISCUSSION

The plant communities at Harmony Point, Nelson Island, South Shetland Archipelago, Antarctica, were studied based on a total of 2,500 quadrats proportionally distributed across all formations identified. The list of species recorded in the area is as follows (Table 1): 27 Bryophyta, 3 Marchantiophyta, 42 lichen species, two terrestrial macroscopic algae [*Prasiola crispa* (Lightfoot) Kützing and *Prasiola calophylla* (Carmichael ex Greville) Kützing], and one flowering plant (*Deschampsia antarctica*) (Table 1). Surprisingly, *Colobanthus quitensis* (Caryophyllaceae) was not found in this protected area, as also reported by Rodrigues et al. (2019), despite being listed by the ATCM (2022). This species was previously noted by Lindsay (1971), who also did not find it along the northern coast of King George Island, except for a single locality at the southwestern tip of the Fildes Peninsula. Schmitz et al. (2018) likewise did not record this species in their survey of plant communities on the small Half Moon Island. *Colobanthus quitensis* is abundant in lower coastal regions, where it forms dense communities and occupies large areas associated with *Deschampsia antarctica* throughout the South Shetland Islands (Schmitz et al., 2018; Vera, 2011). Both species are less common in inland areas and, at the highest altitudes, occur only at restricted sites that are frequently snow-free in the early austral summer (Vera, 2011). Vera (2011) reported the occurrence of *C. quitensis* on Livingston Island and suggested that its distribution there is influenced by the island's geomorphology. Its dispersal is facilitated by nesting skuas but may also occur through strong winds. These conditions are common in Maritime Antarctica, suggesting that this species depends on specific environmental factors for its establishment.

Deschampsia antarctica was found in only two small areas and within two old bird nests: one belonging to a skua (*Stercorarius* spp.) and another to a kelp gull (*Larus dominicanus*). This finding is remarkable, as the population is extremely small, and the plant fragments appear to have been transported to the nests from distances of approximately 150 and 220 m. The use of this species as nesting material has been reported throughout Maritime Antarctica, and its limited local availability still prompts birds to collect it, suggesting a close ecological relationship (Putzke et al., 1989).

Some lichen species commonly found on other South Shetland Islands (Spielman & Pereira, 2012) were extremely rare in the study area, such as the fruticose *Sphaerophorus globosus* (Huds.) Vain. Furthermore, no *Cetraria* species were observed. The fruticose lichens *Usnea* spp. were sterile at all surveyed sites and were predominantly found in their muscicolous growth form. The plant formations identified in the area are discussed below and are represented on the maps (Figures 3–8). To facilitate a better understanding of the plant communities, each area is examined separately (Figure 2).

Beach 1 Area

The marine terrace surrounding the Argentine Refuge Gurruchaga, referred to here as the Beach 1 Area, consists of a highly saturated moss carpet located on the northern/northeastern side of the refuge. The area spans approximately 450 × 150 m and receives water from a permanent ice field (Figure 3). About 35.71% of the area is directly influenced by the sea, which severely limits plant development; vegetation is almost entirely absent in this zone, except for some *Verrucaria* spp. In the remaining 64.29%, sediment displacement, either from human trampling around the refuge or from water flow, has further restricted vegetation growth in 7.14% of the area, leaving 57.15% covered by some type of plant formation (Table 2).

The moss carpet is notably thick, reaching up to 30 cm in depth in certain areas. Additionally, small water ponds bordered by *Bryum* spp. (1.38% cover) and/or *Brachythecium austrosalebrosum* (0.43%) are present. *Warnstorfia* spp. (14.8%) are also found, dominating the central portion of the carpet and occurring in association with *Sanionia uncinata* and *Sanionia georgicouncinata* (Table 2). Together, *Sanionia* spp. constitute 33.01% of the moss carpet, although distinguishing between species in the field is challenging, especially given their frequent co-occurrence with *Warnstorfia* spp. Only one living specimen of *Deschampsia antarctica* was observed, found inside a former skua nest (*Stercorarius* sp.).

In the shallow soils of the southern areas, *Sanionia uncinata* carpets are partially colonized by *Bryum* spp., which alters the community's color to a dull green and receives nutrient input primarily from fur seals (*Arctocephalus gazella*).

TABLE 1 – List of species identified in Harmony Point (ASPA 133), Nelson Island, Antarctica.

Family	*Group*	*Species*
Poaceae	Grass	*Deschampsia antarctica* Desv.
Amblystegiaceae	Moss	*Sanionia uncinata* (Hedw.) Loeske
	Moss	*Sanionia georgicouncinata* (Müll. Hal.) Ochyra & Hedenäs
	Moss	*Warnstorfia sarmentosa* (Wahlenb.) Hedenäs
	Moss	*Warnstorfia fontinaliopsis* (Müll. Hal.) Ochyra
Andreaeaceae	Moss	*Andreaea depressinervis* Card.
	Moss	*Andreaea gainii* Card.
	Moss	*Andreaea regularis* Muell.
Bartramiaceae	Moss	*Bartramia patens* Brid.
Brachytheciaceae	Moss	*Brachythecium austrosalebrosum* (Müll. Hal.) Kindb.
Bryaceae	Moss	*Bryum argenteum* Hedw.
	Moss	*Bryum nivale* Müll. Hal.
	Moss	*Bryum dichotomum* Hedw.
	Moss	*Bryum sp.*
	Moss	*Pohlia cruda* (Hedw.) Lindb.
	Moss	*Pohlia nutans* (Hedw.) Lindb.
Ditrichaceae	Moss	*Ceratodon purpureus* (Hedw.) Brid.
Grimmiaceae	Moss	*Schistidium antarctici* (Card.) L.I. Savicz & Smirnova
	Moss	*Schistidium urnulaceum* (Müll. Hal.) BG Sino
Polytrichaceae	Moss	*Polytrichastrum alpinum* G.L. Smith
	Moss	*Polytrichum juniperinum* Hedw.
	Moss	*Polytrichum piliferum* Hedw.
Pottiaceae	Moss	*Hennediella heimii* (Hedw.) Zand.
	Moss	*Hennediella antarctica* (Angstr.) Ochyra
	Moss	*Syntrichia magellanica* (Mont.) RH Zander
	Moss	*Syntrichia saxicola* Zander
	Moss	*Syntrichia filaris* (Müll. Hal.) Zander
Seligeraceae	Moss	*Dicranoweisia* (*Hymenoloma*) *grimmiacea* (Müll. Hal.) Broth
Cephaloziaceae	Liverwort	*Cephalozia badia* (Gottsche) Steph.
Cephaloziellaceae	Liverwort	*Cephaloziella varians* (Gottsche) Steph.
Lepidoziaceae	Liverwort	*Hygrolembidium isophyllum* R.M. Schust.
Prasiolaceae	Chlorophyta	*Prasiola crispa* (Lightfoot) Kützing
		Prasiola calophylla (Carmichael ex Greville) Kützing
Thelenellaceae	Lichen	*Microglaena antarctica* IM Lamb
Verrucariaceae	Lichen	*Verrucaria* sp.
	Lichen	*Cystocoleus niger* (Huds.) Har.

TABLE 1 (*continuation*) – List of species identified in Harmony Point (ASPA 133), Nelson Island, Antarctica.

Family	*Group*	*Species*
Acarosporaceae	Lichen	*Acarospora macrocyclos* Vain.
Bacidiaceae	Lichen	*Bacidia* sp
	Lichen	*Bacidia tubercullata* Darb.
Physciaceae	Lichen	*Buellia latemarginata* Darb.
	Lichen	*Buellia nelsoni* Darb.
	Lichen	*Buellia russa* (Hue) Darb.
	Lichen	*Buellia anisomera* Vain.
	Lichen	*Buellia* sp
	Lichen	*Physconia muscigena* (Ach.) Poelt
	Lichen	*Physcia caesia* (Hoffm.) Hampe ex Fürnr.
Candelariaceae	Lichen	*Candelaria murrayi* Poelt
Cladoniaceae	Lichen	*Cladonia rangiferina* (L.) Weber ex F.H. Wigg.
	Lichen	*Cladonia furcata* (Huds.) Schrad.
	Lichen	*Cladonia* sp.
Collemataceae	Lichen	*Leptogium puberulum* Hue
Haematommataceae	Lichen	*Haematomma eryhtromma* (Nyl.) Zahlbr.
Lecanoraceae	Lichen	*Lecanora skottsbergii* Darb.
	Lichen	*Rhizoplaca aspidophora* (Vain.) Redon
	Lichen	*Rhizoplaca melanophthalma* (Ram.)Leuckert & Poelt
Lecideaceae	Lichen	*Lecidea sciatrapha* Hue
	Lichen	*Lecidea* sp.
Ochrolechiaceae	Lichen	*Ochrolechia frigida* (Sw.) Lynge
	Lichen	*Ochrolechia parella* (L.) A. Massal.
Pannariaceae	Lichen	*Pannaria hookeri* (Borrer) Nyl.
	Lichen	*Psoroma cinnamomeum* Malme
	Lichen	*Psoroma hypnorum* (Vahl) Gray
Parmeliaceae	Lichen	*Himantormia lugubris* (Hue) Cordeiro IM
	Lichen	*Parmelia saxatilis* (L.) Ach.
	Lichen	*Usnea antarctica* Du Rietz
	Lichen	*Usnea aurantiacoatra* (Jacq.) Bory
Ramalinaceae	Lichen	*Ramalina terebrata* Hook. f. & Taylor
	Lichen	*Lecania brialmontii* (Vain). Zahlbr.
Rhizocarpaceae	Lichen	*Rhizocarpon geographicum* (L.) DC.
	Lichen	*Rhizocarpon polycarpum* (Hepp) Th. Fr.
Sphaerophoraceae	Lichen	*Sphaerophorus globosus* (Huds.) Vain.
Stereocaulaceae	Lichen	*Stereocaulon sp.*
Teloschistaceae	Lichen	*Caloplaca regalis* (Vain.) Zahlbr
	Lichen	*Caloplaca cinericola* (Hue) Darb.
	Lichen	*Xanthoria elegans* (Link) Th. Fr.

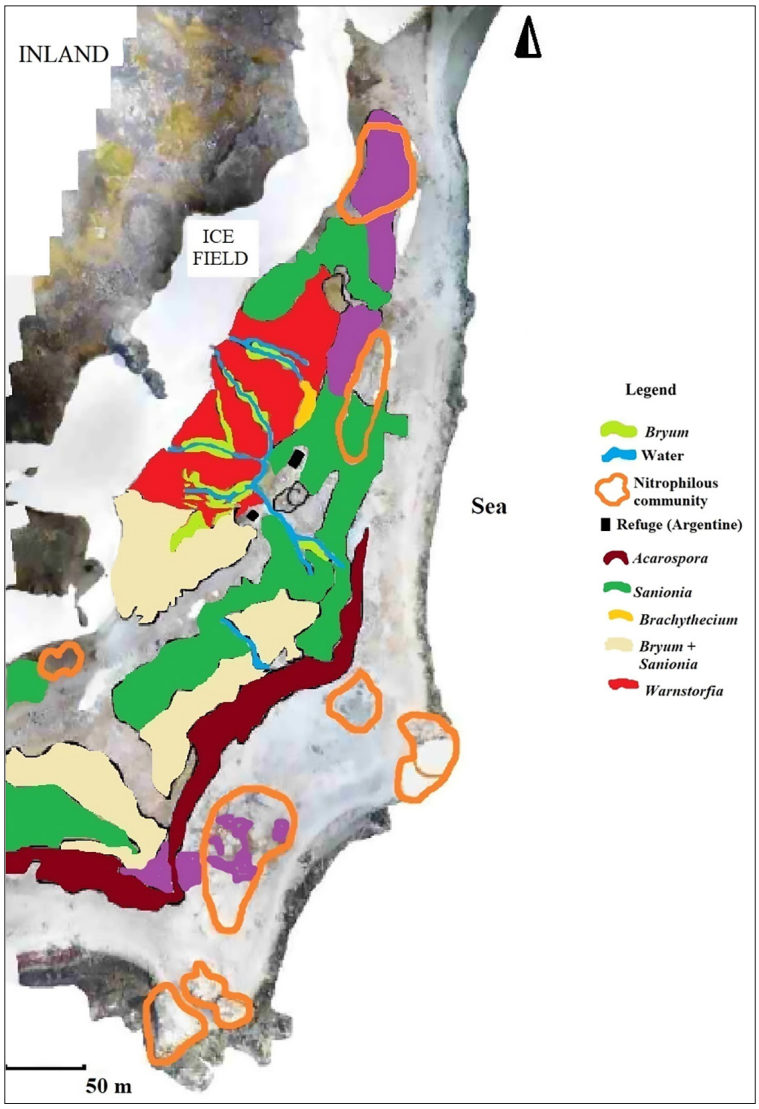

FIGURE 3 – Dominant plant species observed in the vegetation communities of Beach 01.

TABLE 2 – Coverage different species of mosses and lichens in the Beach 01 area.

Species	*Covering in all the Beach 01 area (%)*	*Covering in the carpets (%)*
Sanionia spp.	3.10	33.01
Bryum spp + *Sanionia* spp.	2.44	25.98
Warnstorfia spp.	1.39	14.80
Acarospora macrocyclos	1.24	13.21
Prasiola crispa	1.05	11.18
Bryum spp	0.13	1.38
Brachythecium	0.04	0.43
Total	9.39	99.99

This community, which covers approximately 25.98% of the area, is difficult to distinguish during vegetation mapping. Fur seals were frequently observed in February, and their impact on the moss carpets was evident through fecal deposition and physical compression caused by resting behavior. The effects of fur seal trampling on the vegetation of Signy Island have been studied by Favero-Longo et al. (2011), who concluded that such disturbance can lead to the destruction of muscicolous-terricolous lichens. In contrast, the effects observed here appear to be positive, as nutrient enrichment from seal activity supports the moss community. The association between *Sanionia* and *Bryum* may increase the carpet's resistance to disturbance and seems to inhibit the establishment of muscicolous lichens.

Two very distinct muscicolous communities were found: one to the northeast of the refuge, dominated by *Ochrolechia frigida*, and another to the south, where *Cladonia* spp. dominate. The reasons for this disjunct distribution are not well understood, but it may reflect different stages of community succession. Fur seals are unable to access these communities due to the steep slope of the terrain.

The presence of nesting giant petrels (*Macronectes giganteus*) contributes to a shift in saxicolous lichen communities toward ornithocoprophilous assemblages on rocky substrates (skeletal soils). The occurrence of *Haematomma erythromma*, *Acarospora macrocyclos*, and other crustose and foliose lichens characterizes these areas. *Acarospora macrocyclos* is dominant on the first marine terrace, covering nearly all small rock fragments and accounting for 13.21% of the total plant cover in the Beach 1 Area. This community also receives nutrient input from petrels, as well as from visiting penguins and marine seals (Figure 3). Numerous isolated rocks (approximately 3 m in diameter and 2 m high) support fruticose lichens, particularly *Usnea aurantiacoatra* and *Ramalina terebrata*. The green alga *Prasiola crispa* is found in water ponds within moss carpets and in areas surrounding *Macronectes giganteus* nesting sites. This species is primarily observed near bird colonies, where soils are enriched with guano, a substrate with high concentrations of uric acid and nitrogen compounds (Kovačik & Pereira, 2001).

Weddell seals (*Leptonychotes weddellii*) were observed, occasionally in groups of up to 40 individuals, resting on the permanent glacier ice on the northern side but were rarely present on the studied beach. They appear to have little direct influence on vegetation composition, except for contributing to nutrient flow at the base of the glacier, where *Prasiola crispa* os found growing.

Beach 02 Area:

This area, contiguous with Beach 01 described above, features a large but discontinuous moss carpet on the eastern side, while *Prasiola* is the dominant formation on the western side, covering 0.41% of the total area and representing the second most common plant species in this sector. Only small fragments of a *Bryum*-dominated formation, associated with *Ceratodon purpureus*, occur near an ice field.

This area also contains a unique *Deschampsia antarctica* (Antarctic hair grass) formation surrounding a shallow lake, although it represents only 1.08% of the plant formations on this beach. The grass is established along the line marking the lake's highest water level on the eastern side, influenced by glacier meltwater from the northern slope. The site lies approximately 50–70 m from the seashore and is tolerant to salinity, as previously reported by several authors (Smykla et al., 2007; Ruhland & Krna, 2010).

The first marine terrace features a broad band dominated by *Acarospora macrocyclos*, accounting for 10.79% of the total plant cover in this area. This species occurs alongside other crustose nitrophilous lichens associated with *Macronectes giganteus* (giant petrel) nests, receiving nutrient input from marine animals that promote the establishment of this nitrophilous community (Figure 4). Just beyond this terrace, a 200 m long and up to 2 m wide band of *Stereocaulon glabrum* borders the southern side of the lake. This peculiar formation is rare in Antarctica, with reported coverages of only about 3% in some carpets on Elephant Island (Putzke & Pereira, 2012). According to Lewis-Smith and Øvstedal (1991), in South Georgia and Antarctica, *S. glabrum* typically forms isolated aggregations, occasionally reaching 50 cm across and only rarely covering several square meters.

The plant carpets near the glacier front include extensive formations of muscicolous lichens, particularly *Ochrolechia frigida*, which accounts for 5.03% of the total plant cover. These areas exhibit the characteristic white appearance of this species, sometimes forming patches up to 50 m in diameter. Some of the meltwater streams

originating from the seasonal snowpack are partially covered by *Prasiola crispa*, suggesting that guano input results from its accumulation on the snow, transported by wind and by runoff from the *Macronectes giganteus* nesting site located at the top of the ice field.

In this area, *Sanionia uncinata* dominates the carpets, covering 41.01%, followed by *Warnstorfia* spp. (8.99%) and *Sanionia georgicouncinata* (5.76%) all pleurocarpous mosses, *Bryum* spp. representing 12.6% of the cover, are the main acrocarpous mosses (Table 3) (Putzke & Pereira, 2001).

Beach 03 Area:

This area is the first in the sequence with a high density of penguin colonies. *Prasiola crispa* is the dominant species on the first marine terrace, forming extensive mats, sometimes accompanied by exposed rocks covered with *Mastodia tesselata*, its lichenized form (Kovačik & Pereira, 2001). The older terraces, which are free of penguin nests, support extensive moss carpets surrounding two shallow lakes fed by meltwater. These carpets are primarily composed of *Sanionia* spp. (64.76%) and *Warnstorfia* spp. (15.94%), with meltwater

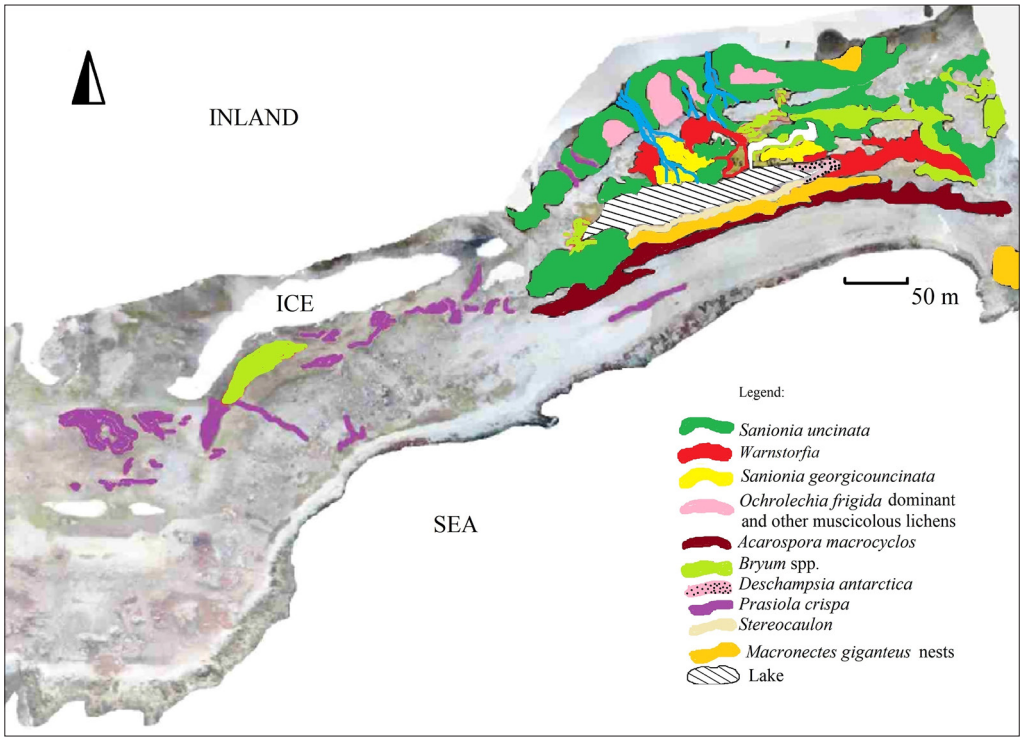

FIGURE 4 – Dominant plant species observed in the vegetation communities of Beach 02.

TABLE 3 – Coverage of different species of mosses and lichens in the Beach 02 area.

Species	*Covering in all the Beach 02 area (%)*	*Covering in the carpets (%)*
Sanionia uncinata	1.14	41.01
Bryum sp.	0.35	12.6
Acarospora macrocyclos	0.3	10.79
Warnstorfia spp.	0.25	8.99
Ochrolechia frigida	0.14	5.03
Sanionia georgicouncinata	0.16	5.76
Deschampsia antarctica	0.03	1.08
Prasiola crispa	0.41	14.7
Total	2.78	

streams bordered by *Bryum* spp. (4.72%). A large muscicolous lichen community is also present, with *Ochrolechia frigida* as the dominant species, typically located in the central, drier portions of the formation (Figure 5, Table 4).

Ornithocoprophilous lichens are commonly found on most of the isolated and larger rocks of the first marine terrace and along the shoreline, where *Verrucaria* spp. are also frequent on the sea-facing sides of the rocks. Three large lakes occur on the first terrace, with three additional ones located near the moss carpets, influencing the composition and structure of the surrounding moss communities.

Beach 04 Area:

The presence of nesting penguins on the uppermost marine terrace limits the development of moss carpets, resulting in areas dominated by ornithocoprophilous communities, where soils are covered only by small colonies of *Prasiola crispa* (Figure 6).

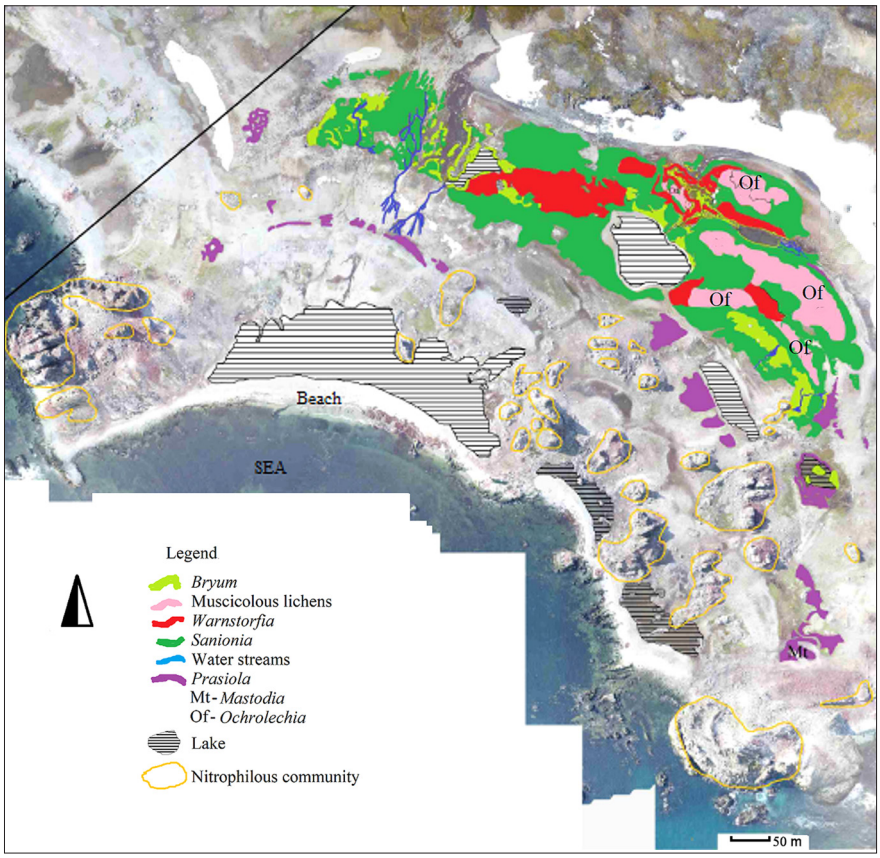

FIGURE 5 – Dominant plant species observed in the vegetation communities of Beach 03.

TABLE 4 – Coverage of different moss and lichen species in the Beach 03 area.

Species	*Covering in the carpet (%)*	*Covering in all the Beach 03 area (%)*
Sanionia spp.	64.76	16.8
Warnstorfia spp.	15.94	4.1
Ochrolechia frigida	14.57	3.8
Bryum spp.	4.72	1.2
Prasiola crispa	Not in the carpet	3.6
Total	99.99	29.5

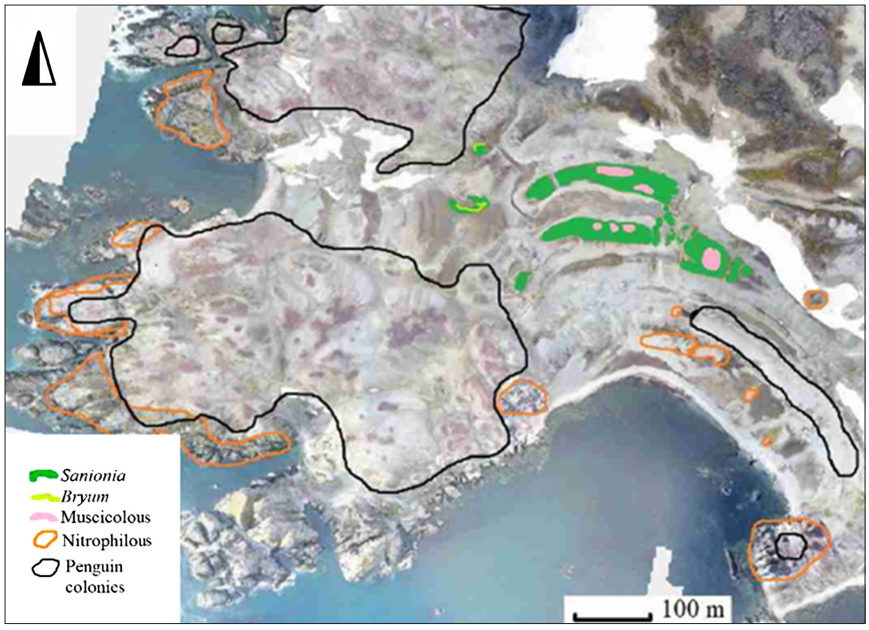

FIGURE 6 – Dominant plant species observed in the vegetation communities of Beach 3. Penguin colonies are highlighted with black circles, and adjacent ornithocoprophilous communities are marked with orange circles.

Rocky cliffs and coastal platforms are also occupied by penguin colonies, with *Prasiola crispa* growing on the soil and nitrophilous lichens colonizing the outer cliff faces (Rodrigues et al., 2019). Moss carpets are found further inland on the third and fourth marine terraces, where they are predominantly composed of *Sanionia uncinata*, representing 92.15% of the carpet composition, and are associated with *Polytrichastrum alpinum*, which forms small, isolated tufts (Table 5). As in other areas, the central portions of the carpets are colonized by muscicolous lichens, mostly *Ochrolechia frigida* (96.71%), forming large circular patches of white thalli ranging from 5 to 20 m in diameter. Smaller moss carpets to the west are bordered by *Bryum* spp. (1.14%).

TABLE 5 – Coverage of different moss and lichen species in the Beach 04 area.

Species	*Covering in the carpet studied (%)*
Sanionia spp.	91.05
Ochrolechia frigida	6.71
Bryum sp.	1.14
Polytrichastrum alpinum	0.10

Southern Plateau

This sector is among the most densely vegetated, characterized by abundant moss carpets, moss cushions, and lichens—most of which are ornithocoprophilous. In the southeastern portion, the landscape forms a complex mosaic of moss species, including carpets of *Sanionia* spp. (4.9%) and *Warnstorfia* spp. (1.83%), as well as cushions of *Andreaea* spp. and scattered clusters of *Polytrichastrum alpinum* and *Chorisodontium acyphyllum*. This high level of biodiversity is likely associated with the availability of water from 16 small, shallow lakes (each up to 10 meters in diameter), which create waterlogged depressions on a cryoplanated platform (Rodrigues et al., 2019).

The margin of the ice deposits leading to Beach 01, located just beyond the glacier front, is predominantly covered by pure cushions of *Andreaea* spp. (1.23%). These cushions gradually transition into muscicolous lichen communities, using *Andreaea* as a substrate. Among the muscicolous lichens, *Himantormia lugubris* occupies a notably large area (1.51%). Turf formations of *Chorisodontium acyphyllum* are found near petrel nests in this sector, likely favored by guano input. The same moss is also observed in thicker formations on hills farther inland, where it grows densely around nesting sites.

The highest plant cover in the sector is formed by *Andreaea* spp. associated with crustose lichens (14.1%), particularly in the northern and central areas. These communities colonize gravel patches devoid of other mosses, including polygonal soils and other exposed mineral surfaces (Figure 7).

Shallow, dry hills are predominantly covered by *Usnea aurantiacoatra*, particularly at higher elevations, where it frequently occurs in association with *Himantormia lugubris*. From a distance, this vegetation formation gives the landscape the appearance of partially burnt coarse grass, as originally described by Lindsay (1971).

Northern Plateau

This area includes a coastal sector with numerous penguin colonies occupying rocky cliffs, where only ornithocoprophilous species develop on rocks not directly affected by bird trampling. Overall, vegetation is poorly developed, particularly in paraglacial zones. Moss carpets dominated by *Sanionia* spp. (67 occurrences) and *Warnstorfia* spp. (8 occurrences) were primarily found on the cryoplanated platform.

Andreaea spp. appears to be the most common moss in the area, sometimes forming dominant cushions independently and sometimes in association with crustose lichens, particularly in patterned ground environments. A notable formation of *Caloplaca* spp. occurs on small rounded rocks accumulated on a marine terrace, forming a distinct contrast with other beaches, where *Acarospora macrocyclos* tends to dominate (Figure 8).

Plant Communities at Harmony Point

Based on the results presented above, seven distinct plant communities were identified at Harmony Point. The first is described below:

i Muscicolous Lichen Community

Two subtypes of this community were distinguished based on the dominant fruticose lichen species:

i.1 Fruticose Muscicolous Lichen Community

This plant formation is the most prominent on the plateau located north of the refuge, occurring on isolated elevated areas and covering approximately 650 m in length and 300 m in width. It may represent one of the most extensive formations of *Himantormia lugubris* in the South Shetland Islands archipelago. This muscicolous lichen, endemic to Antarctica, is primarily associated with *Andreaea* spp. and *Sanionia* spp., forming dark brown, rounded

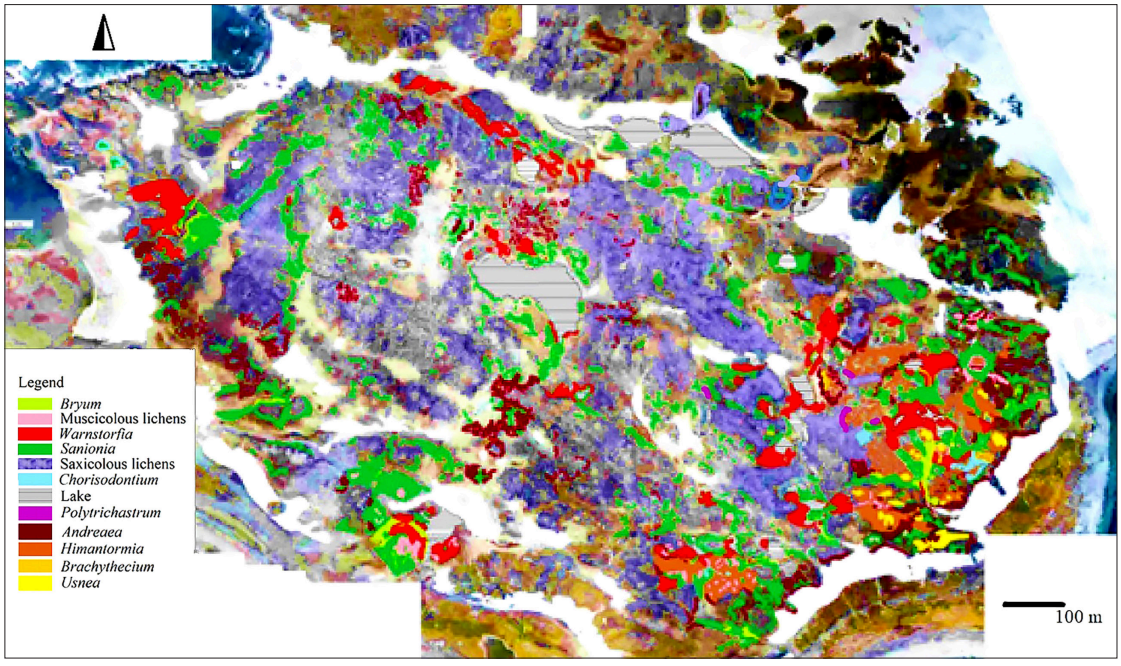

FIGURE 7 – Plant communities identified on the southern plateau of Harmony Point.

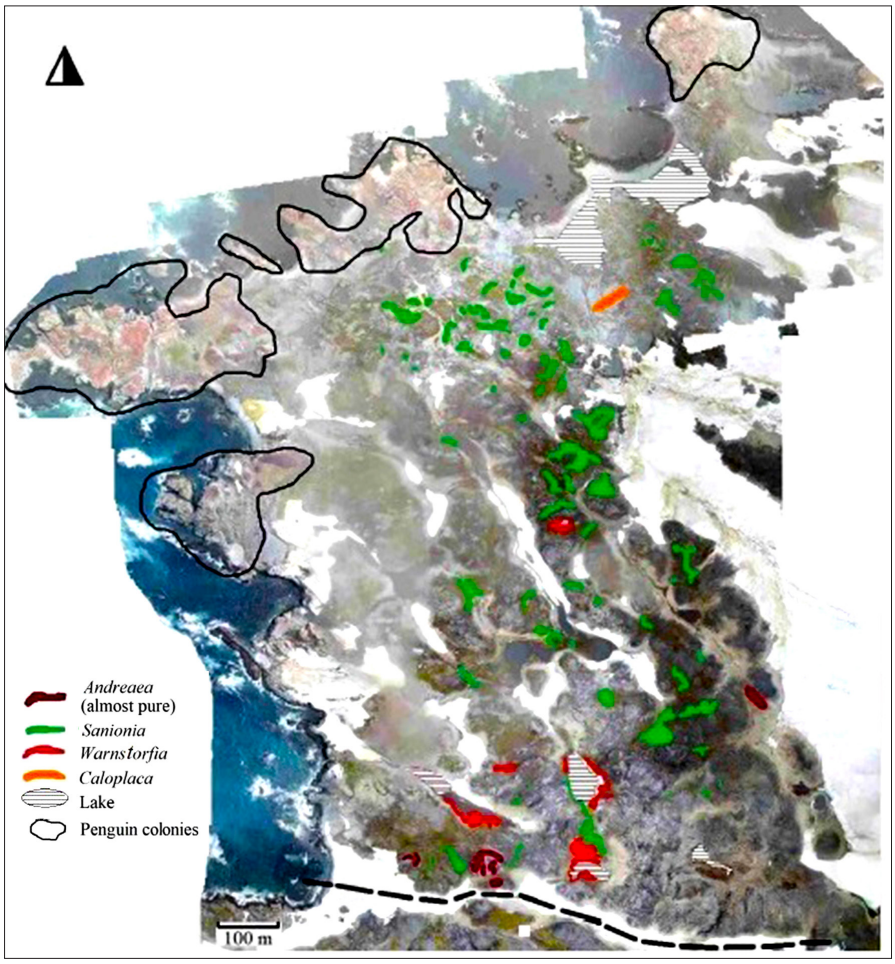

FIGURE 8 – Plant communities observed on the northern plateau of Harmony Point.

or elliptical patches when viewed from above (drone imagery), with diameters reaching up to 35 m.

On shallow hills, sterile *Usnea* spp. (lacking apothecia) many of which are also muscicolous, often occupy the central zone of the patch. This central area is typically surrounded by a prominent ring of *Himantormia lugubris*, followed externally by a zone of *Ochrolechia frigida* growing over *Andreaea* spp. Finally, a peripheral ring of healthy *Andreaea* spp. or *Sanionia uncinata* borders the formation (Figure 9). This zoned structure is here defined as a new plant sociation for Antarctica and is named the *Usnea aurantiacoatra – Himantormia lugubris – Ochrolechia frigida* sociation.

Lindsay (1971) described similar, though less complex, associations, which he referred to as *Usnea–Himantormia* and *Himantormia–Andreaea*. However, he did not mention the circular growth pattern observed in the present study. According to his observations, these communities occur only

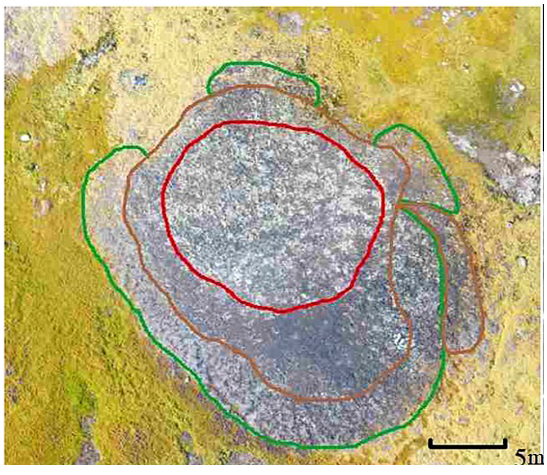

FIGURE 9 – Aerial image showing *Usnea aurantiacoatra* in the central area (outlined in red), surrounded by *Himantormia lugubris* (outlined in brown) and *Ochrolechia frigida* (outlined in green).

at altitudes above 30 m due to the halophobic and nitrophobic nature of the lichens involved, a pattern that is consistent with the conditions found at Harmony Point.

When this formation occurs along the edges of the plateau or on surrounding hills, *Usnea* spp. is often absent, with *Andreaea* spp. forming the external margin and *Ochrolechia frigida* interspersed within the fruticose lichen layer.

Occasionally, *Stereocaulon* spp. is also present within this formation, although the largest continuous occurrence of this genus is found at Beach 2, where it forms a linear pattern occupying several square meters just behind the first marine terrace (Figure 4).

i.2 Foliose/Crustose Muscicolous Lichen Community

The dominant lichen species in this community are *Ochrolechia frigida* (crustose) and *Cladonia* spp. (foliose or squamulose), which are rarely found in association. Occasionally, *Physconia muscigena* is observed growing alongside *Ochrolechia frigida*, or even as the dominant lichen within the community. This is notable because each species forms distinctively colored patches - white (*Ochrolechia*), light green (*Cladonia*), or gray (*Physconia*) resulting in visually distinct, "contaminated" carpets or cushions that are easily recognizable in the field.

The spatial isolation of each dominant muscicolous species is likely related to exposure time, as they share the same moss substrates. Schmitz et al. (2018) reported the co-occurrence of these species on Half Moon Island, although the smaller size of those formations may have increased the likelihood of overlap. In that area, these communities were found on elevated platforms and well-developed soils, with lichens growing over moribund or living mosses, confirming their advanced successional stage and the favorable conditions for the coexistence of some species (Schmitz et al., 2021). At Harmony Point, in the flat area near the field refuge (referred to as Beach 01), *Cladonia* spp. occurs predominantly in the southern section, while *Ochrolechia frigida* dominates the northeastern section, despite both areas sharing similar climatic conditions and substrates. This spatial separation was also observed in all other formations (Figure 10).

ii. Moss Carpet Community

Among the species forming moss carpets at Harmony Point, the most prominent are *Sanionia uncinata*, *Sanionia georgicouncinata*, *Warnstorfia sarmentosa*, *Warnstorfia fontinalopsis*, and *Brachythecium austrosalebrosum*. *Brachythecium* is found primarily along water streams originating from permanent lakes or glacial meltwater, often lining their margins. Its bright green coloration is particularly distinctive in aerial drone imagery. In some lakes, *Bryum* spp. also occur in the wettest surrounding areas. Sacramento et al. (2023), when studying the moss carpets in the northern sector of Harmony Point, reported that this community forms extensive carpets with irregular to undulating surfaces and occurs on dry or humid stable slopes, as well as in hydromorphic flat areas where water accumulates such as flat platforms, waterlogged depressions, and marine terraces.

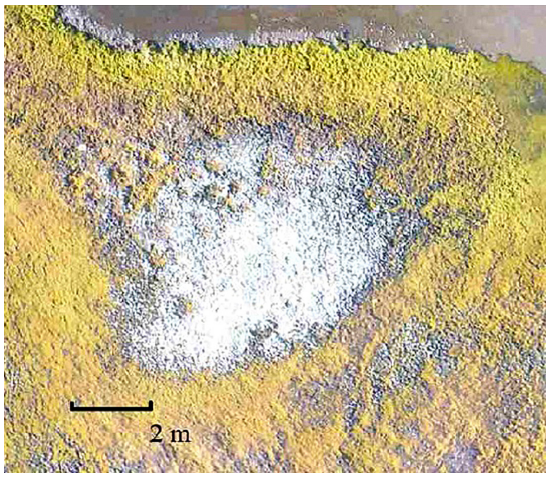

FIGURE 10 – The white *Ochrolechia frigida* community besides Lake 1 in a massive formation.

ii.1 *Warnstorfia* Carpets

The two species of *Warnstorfia* form extensive moss carpets around lakes, meltwater deposits, and water streams. One of the largest formations occurs in the refuge area, where these mosses grow densely. Watercourses crossing the region, originating from an ice field, are initially bordered by *Bryum argenteum*, *Bryum pseudotriquetrum*, and/or *Brachythecium austrosalebrosum*. These carpets may reach depths of up to 30 cm, with high moisture levels being one of their most defining features (Figure 3).

On the southern plateau, east of the refuge, all lakes are at least partially bordered by this community, and in some cases, their margins are almost entirely occupied by *Warnstorfia* mosses (Figure 7).

ii.2 *Sanionia* spp. Carpets

Both species of *Sanionia* occur extensively throughout the study area. *Sanionia georgicouncinata* is typically associated with lakes and meltwater streams, particularly on the southern plateau north of the refuge, where it frequently co-occurs with *Warnstorfia* spp. Interestingly, although the northern plateau has been more recently deglaciated, *Sanionia* carpets occupy a larger area there compared to *Warnstorfia*, despite the abundance of available water.

iii. Crustose Lichen Community

Harmony Point is one of the largest breeding sites for *Macronectes giganteus* (southern giant petrel) in the South Shetland Islands, with more than 480 nests (ATCM, 2022; Krüger, 2019). It also hosts numerous penguin colonies, both of which contribute to the development of nitrophilous crustose lichen communities. These communities are typically found near the coast; however, at Harmony Point, petrel groups also occupy small inland elevations, enabling lichen establishments far from the shoreline. Another notable formation occurs on the first marine terrace near the shoreline. It consists primarily of crustose lichens such as *Bacidia* and *Huea*, associated with *Acarospora* and *Verrucaria*, which give the surface a blackish-brown appearance and form elongated lines along the coast (Figure 2).

On the first terrace of the Northern Plateau, a prominent linear formation of *Caloplaca* spp. is visible along the upper edge. In recently deglaciated areas, a large crustose lichen formation was observed that was not detected through drone imagery, suggesting that this remote sensing method may be inefficient for identifying low-profile lichen cover in Antarctic environments.

iv. Terrestrial Algae Community

Prasiola crispa occurs in various parts of Harmony Point and is often restricted to shallow depressions within *Warnstorfia* spp. carpets, where it may limit the growth of these mosses. In other areas, it grows directly on the soil surface, frequently excluding other species. *Sanionia uncinata* is occasionally found growing in association, particularly along meltwater streams originating from glaciers, where the water is enriched with guano dispersed by strong winds.

In the extreme northern and southern portions of the refuge plateau, two large formations of *Prasiola crispa* receive nutrients from snowmelt mixed with guano and from nearby petrel colonies. At Beach 03, this alga represents the dominant vegetation, especially in areas occupied by bird colonies, since it is a nitrophilous and ornithocoprophilous species that thrives in environments enriched with seabird guano (Kovačik & Pereira, 2001). Interestingly, some moss-bordered zones suggest that *Prasiola* may inhibit moss overgrowth, possibly through allelopathic interactions, although this hypothesis requires further investigation.

v. Moss Turf Community

No extensive formations of *Polytrichastrum alpinum* or *Polytrichum* spp. were found. Instead, only small, rounded colonies, up to one meter in diameter were observed, occasionally surrounding shallow hills. *Polytrichum piliferum* was recorded exclusively on a felsenmeer at the glacier edge, on a hill containing old *Larus dominicanus* nests. According to Sacramento et al. (2023), at Harmony Point, moss turf communities are predominant in protected sites, such as rock crevices of rocky outcrops and talus slopes, as well as in rocky, elevated, and flat terrains like flat platforms and paraglacial areas. *Chorisodontium acyphyllum* was more common on the Southern Plateau, forming some larger patches, but generally occurring as small cushions in competition with carpet-forming mosses near *Macronectes giganteus* nesting areas. All of these species were previously reported by Putzke et al. (1998) at Rip Point, in the northern part of Nelson Island.

vi. Moss Cushion Community

Areas without bird colonies and with persistent snow cover were typically colonized by *Andreaea* spp., forming hemispherical brown to black cushions that often coalesce. These cushions are primarily found on cryoplanated platforms and patterned ground formations across both the Northern and Southern Plateaus (Rodrigues et al., 2019; Sacramento et al., 2023). This is the most widespread plant community at Harmony Point, characterized by dominant or isolated *Andreaea* patches, either alone or in association with lichens and other moss species.

In several locations, *Andreaea* cushions are partially covered by muscicolous lichens, and the moss remains alive only in restricted parts of the cushion. Overall, plant species tend to be free from parasitic lichens, particularly in areas where snow cover persists for longer periods. The cushions are often bordered by *Sanionia uncinata*, which grows

among rocks where *Andreaea* develops, especially in patterned ground zones. *Andreaea gainii* and *A. regularis* are the most common species in this community.

4 CONCLUSIONS

This study presents the most comprehensive floristic and phytosociological survey conducted to date in the Antarctic Specially Protected Area (ASPA No. 133) of Harmony Point, Nelson Island. The identification of 75 plant taxa and seven distinct plant communities reveals a surprisingly high degree of spatial heterogeneity and ecological complexity for a polar environment.

A key contribution of this work is the formal description of a new zonated plant sociation *Usnea aurantiacoatra - Himantormia lugubris - Ochrolechia frigida* which enhances our understanding of Antarctic vegetation dynamics and demonstrates the utility of drone imaging for identifying large-scale cryptogamic formations, despite its limitations in detecting low-profile crustose species.

The findings highlight the strong influence of seabird and seal activity on plant community composition, particularly through guano-driven nutrient enrichment that favors ornithocoprophilous species. In contrast, moss cushions and nitrophobic lichen communities dominate inland, snow-rich, or wind-exposed habitats, illustrating how microhabitats and biotic interactions shape vegetation patterns.

Additionally, the absence of *Colobanthus quitensis*, the rarity of several widespread lichen species, and the sterile condition of *Usnea* spp. underscore the uniqueness of Harmony Point and suggest possible biogeographical or ecological constraints. This study provides essential baseline data for biodiversity monitoring and conservation in Maritime Antarctica and emphasizes the urgency of protecting fragile polar ecosystems in the face of accelerating climate change and increasing human activity in the region.

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