

FLÁVIA RAMOS FERRARI

**SPACE-TIME VARIATIONS OF ENVIRONMENTAL INDICATORS OF
VEGETATION DEVELOPMENT IN ICE-FREE AREAS OF MARITIME
ANTARCTICA**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Botânica, para obtenção do título de *Doctor Scientiae*.

Orientador: Carlos Ernesto G. R. Schaefer

Coorientadores: Marcio Rocha Francelino
Jair Putzke

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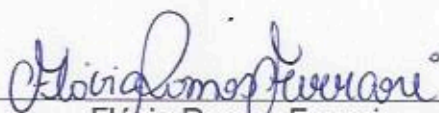
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*Para que meus afilhados e minha
sobrinha conheçam a Antártica através
das minhas palavras*

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RESUMO

FERRARI, Flávia Ramos, D.Sc., Universidade Federal de Viçosa, maio de 2022. **Space-time variations of environmental indicators of vegetation development in ice-free areas of Maritime Antarctica.** Orientador: Carlos Ernesto Gonçalves Reynaud Schaefer. Coorientadores: Marcio Rocha Francelino e Jair Putzke.

A relação entre o ambiente e a forma de crescimento da vegetação se materializa claramente na antártica devido à sua alta sensibilidade às mudanças ambientais. Em escala regional, o clima na Antártica é o principal fator que afeta a diversidade e estrutura da comunidade vegetal, no entanto, em menor escala, a topografia e as propriedades do solo são os fatores mais importantes. Com o aumento da temperatura e posterior recuo das geleiras, novas áreas são expostas. O monitoramento da distribuição da vegetação nessas áreas, dos fatores biogênicos e do recuo das geleiras são fatores-chave que predizem as respostas ecológicas devido às mudanças climáticas. Este estudo teve como objetivo avaliar como as condições ambientais influenciam e interagem com a distribuição das comunidades vegetais, identificando fatores bióticos (aves e composição microbiana do solo) e abióticos (solos, paisagem e gases de efeito estufa) que interferem na dinâmica do ecossistema antártico. Foram visitadas três regiões antárticas distintas no Arquipélago de Shetland do Sul: Thomas Point e Demay Point na Ilha Rei George, e Harmony Point na Ilha Nelson. Assim, mediu-se o potencial de produção de gases de efeito estufa em laboratório de 11 comunidades em um gradiente topográfico, à quatro temperaturas diferentes (-2, 4, 6 e 22 °C). Para avaliar a troca líquida de CO₂ do ecossistema a partir das coberturas do solo, comparar a comunidade microbiana e caracterizar os compostos da matéria orgânica, analisamos coberturas vegetais distintas com sistemas de câmaras claras e amostras de solos. Em três afloramentos rochosos, utilizou-se modelos lineares de efeitos mistos e análises químicas e físicas de solo para avaliar a frequência e cobertura de plantas, padrões de riqueza e os principais efeitos de potenciais preditores. Identificamos 11 comunidades vegetais através de um levantamento fitossociológico, produto ortomosaico com alta resolução a partir de imagens aéreas de drones, e mapeou-se a vegetação média, geleiras e solo no total por meio de classificação manual e *machine learning* usando os modelos preditores avNNet, kkn e rf, baseado em 10 classes. Comparou-se o recuo da geleira e a área total de solo descoberto em três ortoimagens de distintos intervalos de anos. Os resultados mostraram que há uma tendência geral de aumento do potencial de produção de gases de efeito estufa com o aumento da temperatura, com sumidouro de N₂O na maioria das comunidades a -2 °C, e maiores emissões de CH₄ em

tapetes de musgo. A troca líquida de CO₂ no ecossistema apresenta variação entre locais, coberturas vegetais, comunidade microbiana e disponibilidade de fósforo, com maiores emissões de CO₂ devido à matéria orgânica depositada, à diversidade microbiana do solo e à falta de vegetação atual. Descobriu-se que mudanças no substrato ao longo dos afloramentos rochosos também promovem alta rotatividade de espécies entre os três fragmentos rochosos, onde a filtragem mediada pelo habitat pode determinar diferenças na riqueza de espécies. O preditor avNNet teve maior precisão e ao comparar o método automático com o manual de mapeamento, divergindo em diversas situações, mas com o aprendizado de máquina é possível prever áreas livres de gelo e auxiliar os esforços amostrais na Antártica.

Palavras-chave: Comunidades vegetais. Mudanças climáticas. Recuo de geleiras.

ABSTRACT

FERRARI, Flávia Ramos, D.Sc., Universidade Federal de Viçosa, May, 2022. **Space-time variations of environmental indicators of vegetation development in ice-free areas of Maritime Antarctica.** Adviser: Carlos Ernesto Gonçalves Reynaud Schaefer. Co-advisers: Marcio Rocha Francelino and Jair Putzke.

The relationship between the environment and the form of vegetation growth materializes in Antarctic vegetation due to its high sensitivity to environmental changes. On a regional scale, the climate in Antarctica is the main driver that affects plant community diversity and structure, however, on a smaller scale, topography and soil properties are the more important factors. With the increase in temperature and subsequent glacier retreat, new areas are exposed. Monitoring the vegetation distribution, biogenic factors, and the glacier retreat are key factors that predict the ecological responses due to the climate changes. The study aimed to evaluate how environmental conditions influence and interact with the distribution of plant communities, identifying biotic (birds and soil microbial composition) and abiotic (soils, landscape, and greenhouse gases) factors that interfere in the dynamics of the Antarctic ecosystem. This evaluation was conducted in three distinct Antarctic regions in the South Shetland Archipelago: Thomas Point and Demay Point in King George Island, and Harmony Point in Nelson Island. For this, we measure the laboratory greenhouse gases production potential at four different temperatures (-2, 4, 6, and 22 °C), from 11 communities in a topography gradient. To evaluate the net ecosystem CO₂ exchange from soil covers, compare the microbial community, and characterize the compounds of organic matter, we analyzed distinct vegetation covers with light chamber systems and sample soils. In three rocky outcrops, we used linear mixed effect models and soil chemistry and physical analyses to evaluate the plant frequency and coverage, richness patterns, and the main effects of potential predictors. We identify 11 plant communities through a phytosociology survey, product orthomosaic with high resolution from drone aerial images, and mapped the mean vegetation, glaciers, and total bare soil through manual classification and machine learning using the models avNNet, kkn, and rf were predicted, based in 10 classes. We compared the glacier retreating and total bare soil area in three ortho imagens from distant years. Our results showed that there is an overall trend of increasing greenhouse gases production potential with increasing temperature along a toposequence, with N₂O sink in most communities at -2 °C, and the highest CH₄ emissions in moss carpets. Net ecosystem exchange of CO₂ exhibits variation between sites and plant covers, microbial community, and phosphorus availability,

with higher CO₂ emissions due to organic matter deposited, soil microbial diversity, and the lack of current vegetation. We found that changes in the substrate along the outcrops presumably also promote high species turnover between the three rocky fragments, where habitat-mediated filtering can determine species richness differences. The avNNet predictor had higher accuracy and when comparing the automatic with the manual method of mapping, they diverge in diverse situations, but machine learning is possible to predict ice-free areas and help the field efforts in Antarctica.

Keywords: Plant communities. Glacier retreat. Climate change.

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INTRODUÇÃO GERAL

As condições singulares de crescimento da cobertura vegetal no ambiente antártico impõem limites fisiológicos de sobrevivência (ROBINSON; WASLEY; TOBIN, 2003) e demonstram fortes adaptações ambientais. Restrita às áreas livres de gelo, a distribuição da vegetação e sua evolução estão altamente correlacionadas aos fatores bióticos e abióticos (CALLAGHAN; SONESSON; SOMME, 1992; CANNONE et al., 2012; ROBINSON; WASLEY; TOBIN, 2003) e por serem sensíveis às perturbações de seu equilíbrio ambiental, tornam-se importantes indicadores para estudos sobre mudanças climáticas (GUGLIELMIN; EVANS; CANNONE, 2008; TURNER et al., 2005). Limitada quase inteiramente a espécies criptogâmicas (PUTZKE; PEREIRA, 2001), a flora antártica experimenta condições de crescimento sob baixas temperaturas, por curto período de tempo, clima fortemente sazonal, luz contínua no verão e ventos frequentemente fortes. Assim, é composta prioritariamente por briófitas, líquens, fungos macroscópicos e duas espécies de angiospermas (OCHYRA; SMITH; BEDNAREK-OCHYRA, 2008; OLECH, 2002; OVSTEDAL; SMITH, 2001; PUTZKE; PEREIRA, 2001), onde a relação entre o ambiente e a forma de crescimento se materializa claramente na vegetação antártica (LONGTON, 1979).

As alterações ambientais resultam em substanciais e rápidas mudanças no ambiente e podem ser vistas em estudos como Smith (2001), que relatou resultados a longo prazo sobre respostas da colonização de plantas às mudanças climáticas, incluindo consequências ecológicas e fisiológicas, como o aumento das condições favoráveis para colonização, o desenvolvimento, reprodução e dispersão de comunidades, potencial de estabelecimento de novas espécies, até mesmo plantas vasculares, e mudanças na estabilidade devido às mudanças na dominância e/ou abundância de espécies e composição. Kejna et al. (2013) demonstraram que as mudanças ambientais na Ilha Rei George são correlacionadas com mudanças na temperatura da superfície dos oceanos e da concentração de gelo marinho e Robinson et al. (2018) observaram rápidas mudanças na composição de espécies a partir de alterações microclimáticas, em que musgos experimentaram condições menos submersas devido à drenagem da área, impactando o balanço hídrico.

Essa característica de grande sensibilidade dos ecossistemas terrestres da Antártica às alterações climáticas respalda também na dinâmica do carbono. As extensas comunidades vegetais da região polar apresentam papel fundamental na troca de CO₂ (MENDONÇA et al., 2010), interligando os fatores de armazenamento de carbono do solo, degradação microbial da

matéria orgânica (BÖLTER, 1989) e disponibilidade atmosférica (THOMAZINI et al., 2016). Quantificar os gases de efeito estufa e como as áreas livres de gelo é permitir a compreensão dos potenciais mecanismos de fonte/dreno e suas correlações com o ambiente (METZ et al. 2007), além da necessária expansão dessa compreensão para as novas áreas livres de gelo decorrentes das retrações glaciais (FRANCELINO et al., 2011).

Fortemente relacionadas com as propriedades dos solos ao longo da paisagem, as comunidades vegetais demonstram ser conduzidas também pelas características dos mesmos (DURÁN et al., 2021; FERRARI et al., 2021; MICHEL et al., 2006). A forma mais comumente descrita é a relação entre locais de nidificação de aves marinhas e a vegetação associada (MICHEL et al., 2006; SIMAS et al., 2007; TATUR; MYRCHA, 1989). Nesses locais de nidificação, alguns fatores influenciam mais fortemente (ABAKUMOV et al., 2016): (1) o impacto mecânico das aves no solo e na vegetação, em que Smykla et al. (2007) encontraram somente a macroalgae *Prasiola crispa* (Lightfoot) Menegh. em locais cobertos por guano fresco; (2) as alterações na composição química do solo com influência alóctone, onde nutrientes como fósforo e zinco de solos ornitogênicos abandonados podem ser fornecidos à vegetação recente (TATUR; MYRCHA, 1989); bem como a (3) transferência mecânica de esporos através do fluxo das aves, evidenciado por Abakumov et al. (2016). A partir do forte impacto dos pinguins ao ambiente do entorno, Smykla et al. (2007) mostraram a ocorrência de zonas de vegetação menos distintas e mais complexas com o aumento da distância das colônias de pinguins, enquanto Leishman; Wild, (2001) mensuraram a alta diversidade de líquens e musgos e a alta abundância de líquens em locais adjacentes quando comparados aos locais afastados dos ninhais.

Os fatores que influenciam principalmente o crescimento e distribuição de briófitas ainda são debatidas (SUN et al., 2013). Seus mecanismos ecológicos de riqueza e padrão de distribuição de espécies ao longo de gradientes ambientais ainda precisam ser melhor investigados. Os solos são registrados atuando como filtros ambientais determinantes à alta beta diversidade, onde a textura do solo afeta a composição de espécies vegetais antártica (SCHMITZ et al., 2020) e são explicativos de métricas de diversidades filogenéticas através da variabilidade das propriedades físicas relacionadas à textura do solo (CAMPOS et al., 2022). Além disso, demonstrarem a importância da filtragem ambiental na formação dos padrões locais de diversidade ao longo dos gradientes de recursos (LALIBERTÉ; ZEMIMIK; TURNER, 2014).

Compreender os fatores que afetam a distribuição da vegetação em áreas livres de gelo podem auxiliar no estudo das mudanças climáticas em maior escala, avaliando a sua dinâmica temporal e suas relações ecológicas com atributos do meio físico (SCHAEFER, et al., 2004). Sabe-se que investigações de potenciais impactos sobre a biodiversidade requerem conhecimento da riqueza e distribuições reais de organismos nas regiões polares (BARNES; KAISER, 2007). Através da realização do mapeamento florístico e da comparação da biodiversidade do passado recente com a atual pode lançar luz sobre a percentagem de cobertura vegetal e evolução de novas populações e comunidades nessas regiões (SINGH; PEREIRA; RAVINDRA, 2010).

Dessa forma, o presente trabalho tem como objetivo avaliar como as condições ambientais influenciam e interagem com a distribuição das comunidades vegetais, identificando fatores bióticos e abióticos de interferência na dinâmica desse ecossistema. Para isso, este trabalho foi dividido em duas partes. A primeira com dois capítulos sobre a dinâmica de gases do efeito estufa e sua relação com a vegetação e o solo, e a segunda parte, com dois capítulos abordando a riqueza, diversidade e mapeamento de espécies vegetais em áreas livres de gelo. Os capítulos foram intitulados da seguinte forma:

Parte 1:

- Capítulo 1: “Potential greenhouse gases emissions by different plant communities in maritime Antarctica”
- Capítulo 2: “Net ecosystem exchange of CO₂ and interplays with soil, microbial composition and vegetation at maritime Antarctica”

Parte 2:

- Capítulo 3: “Habitat and soil-mediated filtering affect diversity in plant communities of Harmony Point – Nelson Island”
- Capítulo 4: “Classification of ice-free areas: machine learning algorithms combined with the study of vegetation in areas of glacial retreat”

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PARTE 1
CAPÍTULO I:
Potential greenhouse gases emissions by different plant communities in maritime
Antarctica

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ABSTRACT

FERRARI, Flávia, D.Sc., Universidade Federal de Viçosa, May, 2022. **Potential greenhouse gases emissions by different plant communities in maritime Antarctica.** Adviser: Carlos Ernesto Gonçalves Reynaud Schaefer. Co-adviser: Marcio Rocha Francelino and Jair Putzke.

Antarctic plant communities show a close relationship with soil types across the landscape, where vegetation cover changes, biological influence, and soil characteristics can affect the dynamic of greenhouse gases emissions. Thus, the objective of this study was to evaluate greenhouse gases emissions in lab conditions of ice-free areas along a topographic gradient (from sea level up to 300 meters). We selected 11 distinct vegetation compositions areas and assessed greenhouse gases production potentials through 20 days of laboratory incubations varying temperatures at -2, 4, 6, and 22 °C. High N₂O production potential was associated with the Phanerogamic Community under the strong ornithogenic influence (phosphorus, nitrogen, and organic matter contents). Seven different areas acted as N₂O sink at a temperature of -2 °C, demonstrating the impact of low-temperature conditions contributing to store N in soils. Moss Carpets had the highest CH₄ emissions and low CO₂ production potential. Fruticose Lichens had a CH₄ sink effect and the highest values of CO₂. The low rate of organic matter provided the CO₂ sink effect on the bare soil (up to 6 °C). There is an overall trend of increasing greenhouse gases production potential with increasing temperature along a toposequence.

Keywords: Antarctic vegetation. Climate changes. Cryptogamic communities. Greenhouse gas production.

1. INTRODUCTION

The environmental conditions in Antarctica, such as low temperatures, high wind speeds, excessive UV-B radiation, and aridity are limiting for plant growth and survival (Longton 1979), with strong influence on soil properties and distribution (Bockheim 2015). Restricted to ice-free areas of maritime Antarctica, the vegetation cover is mainly cryptogamic communities dominated by lichens, mosses, fungi, algae, and cyanobacteria, mainly forming cryptogamic associations (Smith 1984).

Antarctic biota plays an important role on soil formation in the coastal regions (Bockheim 2015). Microbial transformation of guano is one of the main drivers of ornithogenic soils formation (Schaefer et al. 2008, Simas et al. 2007b, Myrcha & Tatur 1991, Tatur 1989). Considered the most important carbon reservoir in ice-free areas of Admiralty Bay (Simas et al. 2007a), these soil types are rich in organic material and have a wide variation of pH, despite being predominantly acidic (Rodrigues et al. 2021, Schaefer et al. 2008, Simas et al. 2007b, Michel et al. 2006). Nutrients can be also inputted by nutrient cycling from vegetation (Bockheim 2015).

Antarctic plant communities show a close relationship with soil types across the landscape (Durán et al. 2021, Ferrari et al. 2021, Schmitz et al. 2020, Michel et al. 2006). They are indicators of biological responses to rapid environmental changes (Kozeretska et al. 2010, Parnikoza et al. 2009), such as biodiversity decrease or/and changes in species composition (Znók et al. 2017, Robinson et al. 2003), and promote accelerated pedogenetic processes (Almeida et al. 2014, Michel et al. 2014, Schaefer et al. 2008, Simas et al. 2007b). With the increase in temperature and subsequent glacier retreat, new areas are exposed (Cannone et al. 2012, Francelino et al. 2011, Pallàs et al. 1995), where plant succession takes places, in close interplay with environmental variables. This affects the type size, and distribution of plant communities, where increasing plant biomass not just enhance root respiration but also affect the spatial distribution of soil CO₂ emission (Luo et al. 2001, Mendonça et al. 2010), and glacial meltwaters carry a substantial load of microbial cells that may have a profound influence on the composition of terrestrial and marine microbial communities (Znók et al. 2017). Durán et al. (2021) suggests that expected increases in cryptogamic vegetation cover, due to warming conditions, may also result in greater soil organic matter accumulation and enhanced soil fertility.

Soil development and nutrient cycling are the focus of recent studies due to the emerging greenhouse gases (GHGs) potential in Antarctica terrestrial ecosystems (Thomazini

et al. 2015a, Zhu et al. 2014a, Sun et al. 2002). Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are the most important GHGs.

Changes in vegetation cover, biogenic factors (e.g., microbial community), soil temperature and moisture can affect the dynamics of GHGs (Almeida et al. 2014, Mendonça et al. 2010). Thomazini et al. (2015a) suggests that newly exposed land surfaces enhance soil formation with increasing labile carbon (C) input from vegetation, coupled with greater soil CO₂-C emissions. Zdanowski et al. (2005) reported that increased microbial activity may be expected in Antarctic areas where CO₂ emissions from tundra soil are increasing. Significantly higher surface temperature at a rookery penguin was associated with the direct influence of birds, resulting on higher microbial activity coupled with elevated soil temperatures. The temperature is one of the most important factors controlling microbial processes, especially in Antarctica. In this context, carbon emissions can be proxies of regional warming since carbon reservoirs can be mineralized within relatively short periods due to the great lability (Thomazini et al. 2015a).

Soils are important sources or sinks of GHGs in terrestrial ecosystems (Metz et al. 2007). The GHG assessment allows the investigation of possible correlations between soil properties, thermal/hydric dynamic, landscape characteristics and vegetation distribution, indicating and potential mechanisms of GHG sink/emission (Thomazini et al. 2015b). However, little is known about GHGs in ice-free areas of maritime Antarctica. Thus, the objective of this study was to evaluate greenhouse gases production potentials in lab incubations as a function of soil temperature at the main ice-free areas along a topographic gradient on King George Island, maritime Antarctica. We hypothesized that soil characteristics of plant communities and floristic composition will influence GHG emissions across the landscape. We expected increases in soil temperature will enhance GHG emissions.

2. MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The study was carried out in ice-free areas surrounding the Henryk Arctowski Station located in Thomas Point, Admiralty Bay (61°50'S, 62°15'W). This area makes up the Antarctic Specially Managed Area (ASPA) No. 128 (Figure 1a-c). The mean annual air temperature in the station region was -1.2 °C (period summer 2012-2013) (Araźny et al. 2013), and the climatic data acquired at the Brazilian Comandante Ferraz Station nearly points a mean of 400 mm of precipitation (INPE 2015).

The characterization of the area considered the altitudinal difference of the sampled region, representing a toposequence that varies from sea level to the highest peak (300 meters above sea level). Thus, we selected 11 areas according to the vegetation cover and altitude across the landscape (Figure 1c-g; SI).

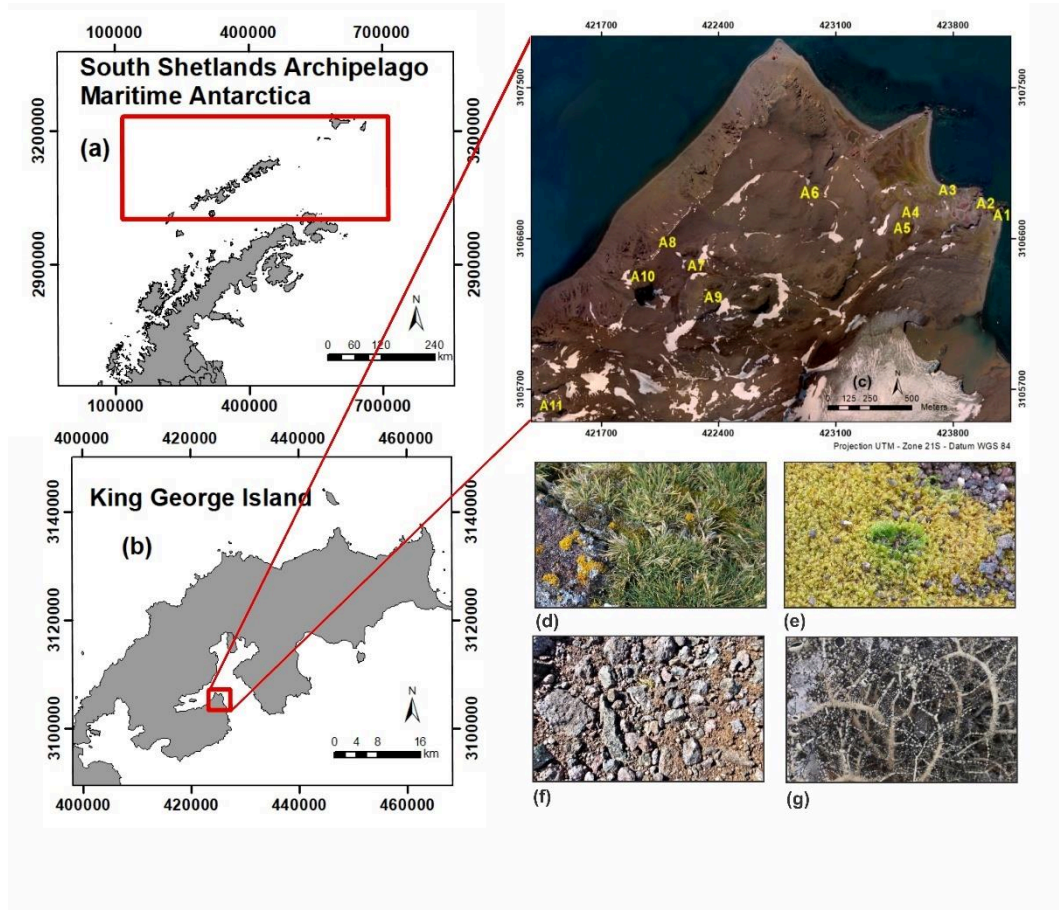


Figure 1. Map of the South Shetlands Archipelago (a), showing the location of King George Island (b) and the studied area near the Polish Henry Arctowski Station (c). Areas 1, 2, and 3: Phanerogamic Community (d); Areas 4 and 7: Moss Carpet Community (e); Area 8: Bare soil (f); Areas 9, 10, and Area 11: Fruticose Lichens Community (g).

2.2 PLANT COMMUNITIES SURVEY

Plant communities were characterized according to their associations in terms of dominant species, based on the phytosociological survey (Braun-Blanquet 1932) adapted for Antarctic conditions by Schmitz et al. (2018). In each of the 11 selected areas we sampled 12 plots of 20 x 20 cm. We calculated the index of ecological significance (IES), coverage and frequency (Lara & Mazimpaka 1998), values that classified plant communities, and their associations.

2.3 SOIL SAMPLING

2.3.1 SOIL GENERAL PROPERTIES

In each phytosociology plot, we collected a soil sample (0-10 cm depth) to evaluate the general soil properties. The analyzes followed international standard protocols (Teixeira et al. 2017). We measured the chemical properties of pH (H₂O), P, K, Na, Ca, Mg, Al³⁺, total acidity (H +Al), bases sum (SB), effective cation exchange capacity (CEC_{eff}), total cation exchange capacity (CECT), saturation of bases (V), aluminum saturation index (m), sodium saturation index (ISNa), organic matter (OM), remaining phosphorus (P-Rem), Cu, Mn, Zn, total nitrogen (N), and carbon (C). The physical properties analyzed were soil texture, classified as sand, silt, and clay contents.

2.3.2. GHG SOIL SAMPLES

We collected one soil sample in each of the 11 areas to measure the laboratory GHG production potentials (at 0-10 cm depth). The samples were air-dried, passed through a 2 mm sieve, stored and identified in plastic bags and sent to the University of Minnesota - USA for the incubation study.

2.3.3 LABORATORY GHG PRODUCTION POTENTIALS

The GHGs production potentials were determined by following an incubation method at field capacity (soil moisture potential = -33 kPa), varying soil temperature (-2, 4, 6, and 22 °C) (Spokas & Reicosky 2009). GHGs production potentials were evaluated on a gas chromatographic-mass spectrometer (GC-MS) system (Agilent, Foster City, CA, model 7694) (Spokas et al. 2009) to quantify gas production over the 20-d incubation period. Triplicate sub-samples (5 g of each one soil sample) were placed in three sterilized 125 mL serum vials (Wheaton Glass, Millville, NJ) and sealed with red butyl rubber septa (Grace, Deerfield, IL). Control incubations were run as the incubation blanks to ensure that no sorption or reaction of the analyzed gases with the serum vial or septa occurred. However, if the O₂ level dropped below 15% (v/v) during the incubation, the incubation was stopped, and the rates of production were calculated up to this point as the linear fit of accumulation of GHGs in the headspace with time to maintain comparison of aerobic conditions across all incubations. An initial 7-day period was allowed for the soil to equilibrate after rewetting (Thomazini et al. 2015a, Fierer & Schimel 2003, Franzluebbers et al. 1996).

2.4 DATA ANALYSES

Soil general properties were interpreted based on descriptive statistics (mean, minimum, maximum, median, coefficient of variation, standard error, asymmetry, and kurtosis). The results of CO₂, N₂O, and CH₄ production potentials were analyzed by the means of triplicate samples, for different temperatures. The N₂O outliers were removed. The sensitivity of GHG production as related to temperature increase was calculated from the difference between -2 °C to 4 °C, -2 °C to 6 °C, and -2 to 22 °C. Carbon dioxide equivalent (CO₂e) was calculated to describe different GHG in a common unit and mean the amount of CO₂ which would have the equivalent global warming impact (GWP) (IPCC 2007). The CO₂e unit measure was transformed from kg to ng.

The principal component analyses (PCA) were performed for each GHG to represent the best general trends on the landscape. The variables were temperatures and sampled areas in the toposequence. We also calculated Pearson correlations among gases and the PCA ordination axes. These analyses were performed to establish the possible relationship between community groups (floristic composition) and the gases production potential, separated according to the geographical position (altitude) along the toposequence. The soil average variables and the GHG average values were run in a PCA to visualize possible soil properties criteria in the gas productions. Spearman's correlation coefficient was calculated to identify correlation values. Extreme values were selected and run separately to find redundant variables within two axes (dim1 and dim2), and GHG values were maintained. All analyses were carried out using the R Environment (R Core Team 2018).

3. RESULTS

3.1 PLANT COMMUNITIES

In total, 132 plots were sampled. These areas are distributed in a range from sea level, up to an altitude of 300 meters (Figure S1) (Table I), and grouped according to floristic similarity with main characteristics of plant composition and landform (Table II). We identified 16 species (Table SIa). The richest family in species was the Parmeliaceae, with three species, followed by Grimmiaceae and Teloschistaceae, both with two species. *Usnea antarctica* Du Rietz was represented in six areas, and often showed high IES values, followed by *Colobanthus quitensis* (Kunth) Bartl, *Deschampsia antarctica* E. Descv, and *Sanionia* spp., which were recorded in five areas; there, *D. antarctica* and *Sanionia* spp. possessed high IES values (Table SIb).

Table I. Areas of study in the vicinity of the Polish Station H. Arctowski, maritime Antarctica region: plant communities and their associations.

Areas	Altitude (m)	Community	Association
1	3	Phanerogamic	<i>Deschampsia</i> - <i>Prasiola</i>
2	5	Phanerogamic	<i>Deschampsia</i> - <i>Colobanthus</i>
3	20	Phanerogamic	<i>Deschampsia</i> - <i>Syntrichia</i>
4	80	Moss Carpet	<i>Sanionia</i> - <i>Bryum</i>
5	83	Phanerogamic	<i>Deschampsia</i> - <i>Sanionia</i>
6	85	Fruticose Lichens	<i>Usnea</i> - <i>Andreaea</i>
7	90	Moss Carpet	<i>Sanionia</i> - <i>Bryum</i>
8	220	Bare soil	-
9	260	Fruticose Lichens	<i>Usnea</i> - <i>Schistidium</i>
10	280	Fruticose Lichens	<i>Himantormia</i> - <i>Usnea</i>
11	300	Fruticose Lichens	<i>Usnea</i> - <i>Schistidium</i>

Table II. Main characteristics of plant communities grouped according to species with higher index of ecological significance (IES).

Areas	Community	Main characteristics
1-2-3-5	Phanerogamic	Mixed communities with higher rates of plant species diversity. Established on uplift marine terraces of different ages. Highly influenced by ornithogenesis.
4-7	Moss carpet	The soil under hydromorphic status, low diversity of plant species, and exclusive composition of mosses. Composed by the same species dominance, but in a different environment: abandoned penguin on the uplifted marine terrace and glacier drainage line in a hanging valley.
6-9-10-11	Fruticose lichens	Areas formed by large boulders on a rocky crest, with discontinuous vegetation. Soils in fractures and depressions, with incipient development. No ornithogenic influence.
8	Bare soil	A hillside with an extensive site of bare soil, virtually without vegetation cover.

3.2 SOIL PROPERTIES AND LABORATORY GHG PRODUCTION POTENTIALS

Table III reported the medians of the 22 chemical soil attributes, and Table IV presents the soil textural data for the 11 sample locations. Table V shows the average GHG production potential observed in the incubations of the 11 sampled areas at four different temperatures,

and Table VI shows the sensitivity of the responses to GHG concentrations between -2 to 4 °C, -2 to 6 °C, and -2 to 22 °C.

The highest N₂O production potential was associated with the Phanerogamic Community - *Deschampsia* – *Prasiola* association (area 1), under strong ornithogenic influence, near the coast (3 m a.s.l), followed by the also Phanerogamic area 3. Both are the areas with the highest phosphorus (1241.15 and 4683.1 mg dm⁻³, respectively) and nitrogen (0.43 and 1.04 dag kg⁻¹, respectively) rates. The same N₂O production pattern was observed with different temperatures, with a maximum value observed at 6 °C (22.58 ng N g_{soil}⁻¹ day⁻¹). On the other hand, seven distinct areas acted as an N₂O sink at a temperature of -2 °C, demonstrating the influence of low soil temperatures contributing to store N in soils (Figure 2a).

Table III. Medians of the soil chemical attributes (0-10 cm depth) along the 11 areas studied in different positions in the landscape.

	1	2	3	4	5	6	7	8	9	10	11
pH	4	4.61	4.38	4.46	4.61	6.77	7.05	7.12	5.83	6.38	6.42
P	1241.15	701.55	4683.1	872.70	814.90	61.30	50.05	73.25	55.90	29.60	53.50
K	246.36	149.50	137.50	140.00	128.50	149.00	141.50	103.00	198.50	191.00	148.00
Na	248.60	389.00	625.75	364.20	298.90	1533.05	1234.35	1488.10	1257.40	1287.50	1287.45
Ca²⁺	4.81	3.66	7.07	2.15	2.03	17.19	25.36	16.54	7.43	10.94	22.39
Mg²⁺	1.49	2.08	2.14	0.77	1.50	9.95	14.10	8.23	8.11	9.69	11.86
Al³⁺	1.78	4.94	0.49	6.56	8.74	0.00	0.00	0.00	0.64	0.10	0.00
H+Al	10.68	16.05	13.60	15.55	22.25	1.70	1.10	1.30	5.00	3.50	1.60
BS	8.35	7.43	13.07	4.71	5.24	34.22	45.02	31.63	22.28	27.00	40.36
CECeff	9.04	11.79	13.57	12.07	14.28	34.27	45.02	31.63	22.68	27.10	40.36
CECT	21.68	24.85	26.18	21.68	26.46	35.72	46.42	32.87	27.42	30.64	42.21
V	36.70	31.55	47.90	23.40	18.15	95.15	97.00	96.05	81.95	88.60	96.15
m	20.40	34.70	3.50	58.55	62.05	0.00	0.00	0.00	2.65	0.40	0.00
ISNa	5.09	6.90	10.28	7.88	4.57	18.44	11.41	19.70	19.70	18.66	13.29
OM	3.88	2.67	9.68	2.07	3.23	1.29	1.29	0.39	2.87	1.83	0.39
P-Rem	54.10	33.35	50.20	25.35	18.50	34.20	36.60	34.85	24.95	22.00	38.45
Cu	10.61	12.10	29.97	7.28	7.22	2.52	4.63	3.51	2.82	2.80	4.27
Mn	3.20	7.00	13.75	4.35	2.10	17.90	44.20	28.10	16.75	2.10	22.00
Fe	322.10	453.30	281.20	257.90	189.20	94.00	180.85	87.05	85.75	93.45	68.70
Zn	6.49	2.57	37.35	1.69	0.82	0.16	0.38	0.16	0.35	0.38	0.26
N	0.43	0.20	1.04	0.13	0.19	0.02	0.01	0.00	0.19	0.09	0.02
C	2.25	1.55	5.61	1.20	1.87	0.75	0.75	0.23	1.66	1.06	0.23

pH: active acidity (H₂O); P: phosphorus (mg dm⁻³); K: potassium (mg dm⁻³); Na: sodium (mg dm⁻³) (extractor Mehlich 1); Ca: calcium (cmol_c dm⁻³); Mg: magnesium (cmol_c dm⁻³); Al³⁺: exchangeable aluminum (cmol_c dm⁻³) (extractor KCl 1 mol L⁻¹); H+Al: total acidity (cmol_c dm⁻³) (extractor calcium acetate 0.5 mol L⁻¹ pH 7.0); BS: bases sum (cmol_c dm⁻³); CECeff: effective cation exchange capacity (cmol_c dm⁻³); CECT: total cation exchange capacity pH 7.0 (cmol_c dm⁻³); V: saturation of bases (%); m: aluminum saturation index (%); ISNa: sodium saturation index (%); OM: organic matter (dag/kg); P-Rem: remaining phosphorus (mg/L); Cu: copper (mg dm⁻³); Mn: manganese (mg dm⁻³); Fe: iron (mg dm⁻³); Zn: zinc (mg dm⁻³); N: total nitrogen (dag kg⁻¹); C: carbon (dag/kg) (Walkley & Black method).

Table IV. Medians of the soil physical attributes (0-10 cm depth) along the 11 areas studied in different positions in the landscape.

	1	2	3	4	5	6	7	8	9	10	11
Sand (%)	75.10	79.15	65.95	79.65	76.65	74.25	68.65	66.70	63.70	64.90	63.35
Silt (%)	10.80	8.20	14.75	8.50	9.90	13.50	14.55	19.45	18.35	19.15	13.40
Clay (%)	14.80	12.20	20.00	11.00	11.45	12.45	15.75	13.90	17.10	17.10	21.25
Class^a	Sandy loam	Loamy sand	Sandy loam	Loamy sand	Loamy sand	Loamy sand	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Soil type^d	1	1	2	1	1	1	1	2	2	2	2

^aSBCS; ^dIN SPA/MAPA 02/2008.**Table V.** Average values of production potentials of N₂O (ngN g_{soil}⁻¹ day⁻¹), CH₄ (ngC g_{soil}⁻¹ day⁻¹), and CO₂ (ugC g_{soil}⁻¹ day⁻¹) in different plant communities along a toposequence.

Temp.	-2 °C			4 °C			6 °C			22 °C		
Site	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂
1	6.36	-0.28	1.05	20.86	-0.38	2.31	22.58	2.38	11.45	20.81	0.19	12.15
2	-0.16	-0.34	0.70	1.65	-0.42	2.54	0.58	1.90	2.48	0.74	0.23	4.44
3	0.28	-0.32	2.09	5.23	-0.39	10.71	2.29	2.63	8.43	6.47	0.24	13.60
4	-0.09	-0.30	0.13	0.65	-0.37	0.57	1.20	2.67	0.96	1.27	0.16	0.63
5	-0.16	-0.37	0.31	0.29	-0.42	1.93	0.83	2.59	1.53	1.18	0.19	1.83
6	1.17	-0.39	0.27	0.43	-0.66	0.47	1.18	2.29	1.57	2.08	-0.09	2.85
7	-0.30	-0.34	0.51	0.48	-0.36	0.73	0.85	2.67	1.14	0.73	0.23	1.77
8	-0.23	-0.32	-0.08	0.38	-0.54	-0.22	0.49	1.54	-0.17	-0.02	-0.02	1.12
9	1.17	-0.21	3.45	1.88	-0.99	6.99	3.13	0.92	7.72	13.65	-0.15	22.08
10	-0.25	-0.39	1.27	0.43	-0.83	1.85	0.46	1.26	3.05	0.69	0.00	9.49
11	-0.09	-0.48	1.17	0.38	-0.93	1.59	0.49	0.99	2.30	0.63	-0.22	6.27

Table VI. The sensitivity of the responses to GHG concentrations with temperature increase. N₂O: ngN g_{soil}⁻¹ day⁻¹; CH₄: ngC g_{soil}⁻¹ day⁻¹; CO₂: ugC g_{soil}⁻¹ day⁻¹.

Temp.	-2 °C → 4 °C			-2 °C → 6 °C			-2 °C → 22 °C		
Site	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂	N ₂ O	CH ₄	CO ₂
1	> 14.5	< 0.1	> 1.26	> 16.22	> 2.66	> 10.4	> 14.45	> 0.47	> 11.1
2	> 1.81	< 0.08	> 1.84	> 0.74	> 2.24	> 1.78	> 0.9	> 0.57	> 3.74
3	> 4.95	< 0.07	> 8.62	> 2.01	> 2.95	> 6.34	> 6.19	> 0.56	> 11.51
4	> 0.74	< 0.07	> 0.44	> 1.29	> 2.97	> 0.83	> 1.36	> 0.46	> 0.50
5	> 0.45	< 0.05	> 1.62	> 0.99	> 2.96	> 1.22	> 1.34	> 0.56	> 1.52
6	< 0.74	< 0.27	> 0.20	> 0.01	> 2.68	> 1.30	> 0.91	> 0.3	> 2.58
7	> 0.78	< 0.02	> 0.22	> 1.15	> 3.01	> 0.63	> 1.03	> 0.57	> 1.26
8	> 0.61	< 0.22	< 0.14	> 0.72	> 1.86	< 0.09	> 0.21	> 0.3	> 1.20
9	> 0.71	< 0.78	> 3.54	> 1.96	> 1.13	> 4.27	> 12.48	> 0.06	> 18.63
10	> 0.68	< 0.44	> 0.58	> 0.71	> 1.65	> 1.78	> 0.94	> 0.39	> 8.22
11	> 0.47	< 0.45	> 0.42	> 0.58	> 1.47	> 1.13	> 0.72	> 0.26	> 5.1

The PCA shows N₂O values strongly correlated with 6 °C ($r = 0.95$; $p < 0.05$), where axis 1 explains a total of 74.6 % of the variance (Fig. 2b). Area 1 is clearly distinguished from other communities in the PCA grouped at 4 and 6 °C, with the biggest increases in sensitivity among all communities (average increase of $15.05 \text{ ngN g}_{\text{soil}}^{-1} \text{ day}^{-1}$), in addition to a weak contribution at -2 °C. The other Phanerogamic Communities were grouped with communities composed of mosses and lichens, not differentiating the N₂O potential floristic composition. When analyzed in the PCA with the soil attributes (Figure 5d) areas 1 and 3 were grouped due to the high values of N, P, and OM, characteristic of ornithogenic areas.

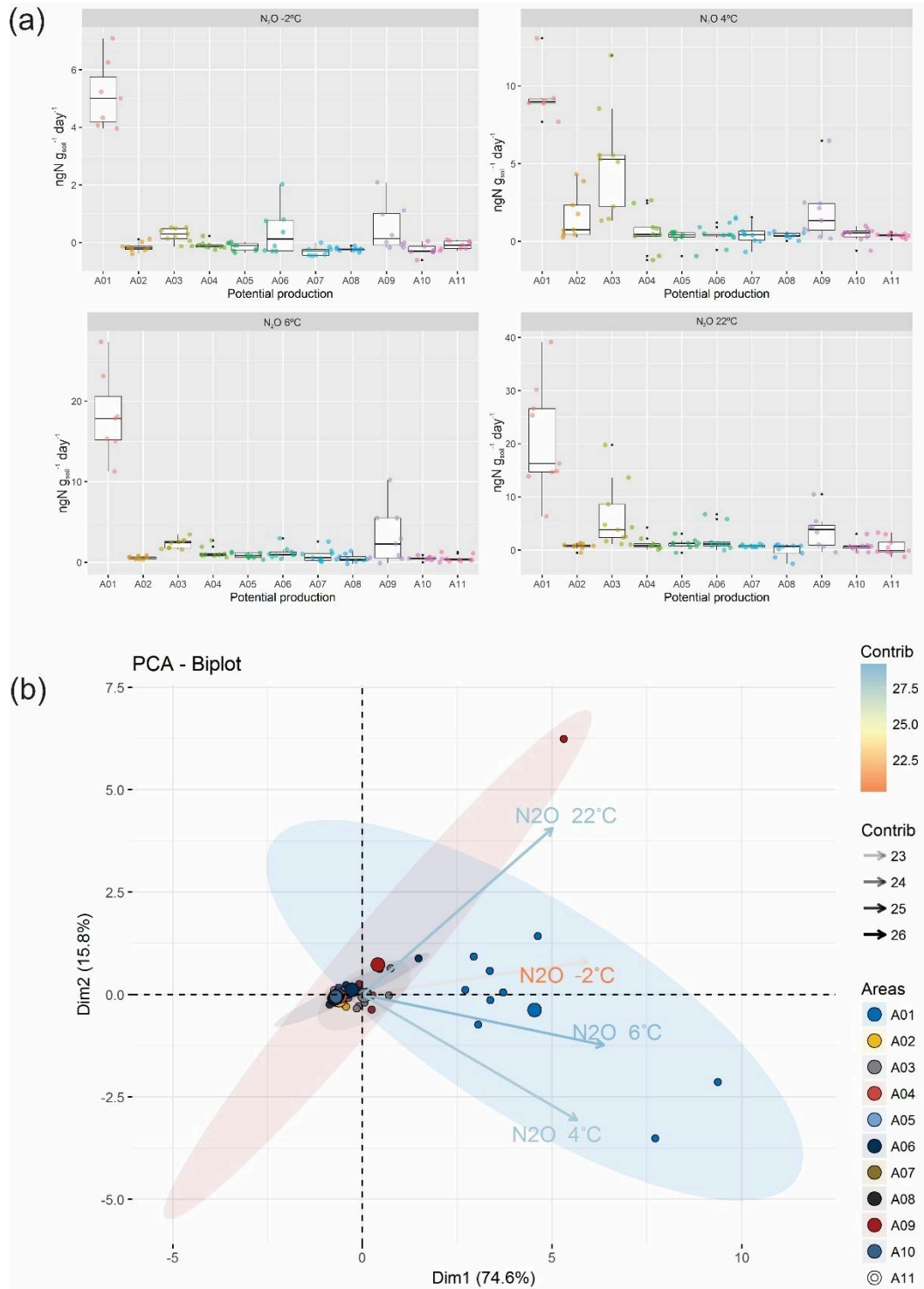


Figure 2. Average values of N_2O production potential at -2 , 4 , 6 , and 22°C , in 11 areas sampled along a toposequence (a). Principal component analyses – PCA indicating good discrimination and grouping of plant communities according to the N_2O soil production values, at temperatures of -2°C , 4°C , 6°C , and 22°C (b).

The CH_4 production potential in lab (Figure 3a) showed high values when temperature increased up to 6°C and a decrease in values at 22°C . The mosses carpets (areas 4 and 7) recorded the highest production potentials ($2.67 \text{ ngC g}_{\text{soil}}^{-1} \text{day}^{-1}$ both), followed by Phanerogamic Communities (areas 3 and 5) (2.63 and $2.59 \text{ ngC g}_{\text{soil}}^{-1} \text{day}^{-1}$). The axis 1 from

PCA (Figure 3b) explain 58.8 % of the variance, positively correlated with 4 °C ($r = 0.94$; $p < 0.05$), 22 °C ($r = 0.90$; $p < 0.05$), and 6 °C ($r = 0.80$; $p < 0.05$), while the axis 2 explain 22.5 %, positively correlated with 2 °C ($r = 0.98$; $p < 0.05$). The Fruticose Lichens Communities (areas 6, 9, 10, and 11), at higher topographic positions in the landscape, revealed a CH₄ sink effect potential, grouped in the opposite from 4 to 22 °C on the PCA (Figure 3b). This pattern was similar to the soil without vegetation cover (area 8), but that registered values closer to zero. When the temperature reached 22 °C, the production potential decreased in all areas, reaching negative values in four areas (areas 6, 8, 9, and 11). The bottom areas of the toposequence were grouped in the opposite with temperatures of 4, 6, and 22 °C. This similarity of sink effect in the Fruticose Lichen Communities and in the bare soil can be explained by the soil chemical properties, when they are grouped in the PCA (Figure 5d) with Na and SB values. With the increase in altitude and change in plant composition, there is a considerable increase in Na rates from area 6 to the top of toposequence (Table III).

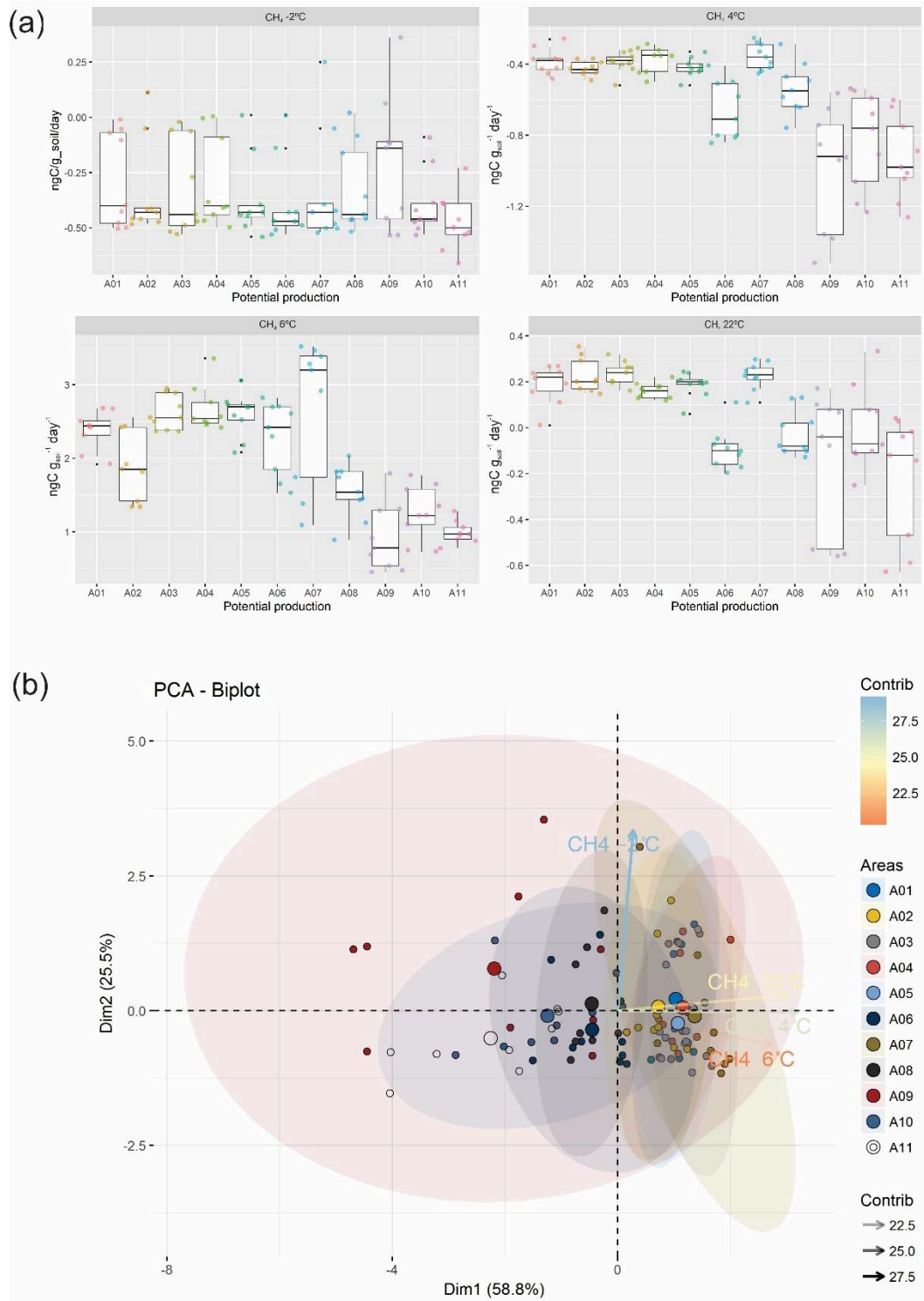


Figure 3. Average values of CH₄ production potential at -2, 4, 6, and 22 °C, in 11 areas sampled along a toposequence (a); Principal component analyses – PCA indicating discrimination and grouping of plant communities according to the CH₄ soil production values, at temperatures of -2 °C, 4 °C, 6 °C, and 22 °C (b).

Results suggested that there is an overall trend on CO₂ production potential with increasing temperature (Figure 4a). The bare soil (area 8) was the only studied area with negative values, considered as a CO₂ sink (-0.08 , -0.22 , and -0.17 $\mu\text{g C g}_{\text{soil}}^{-1} \text{ day}^{-1}$, at -2, 4,

and 6 °C, respectively). However, by increasing temperature to 22 °C, even the bare soil released carbon into the atmosphere ($1.12 \mu\text{g C g}_{\text{soil}}^{-1} \text{ day}^{-1}$), demonstrating the influence of very high temperatures on CO₂ production potential in the Antarctic soils. The Moss Carpets remained with low production potential at all temperatures. Although, the moss floristic composition can also be considered a factor that contributes to the CO₂ source strength.

Greater CO₂ production potentials (Figure 4a) were observed at the highest positions of the toposequence (260 to 300 m a.s.l) at 22 °C (areas 9, 10, and 11), with a maximum in area 9, under Fruticose Lichens Community ($22.08 \mu\text{g C g}_{\text{soil}}^{-1} \text{ day}^{-1}$). The same trend was recorded in the other extreme, at lowest altitude (areas 1, 2, and 3, between 3 and 20 m a.s.l).

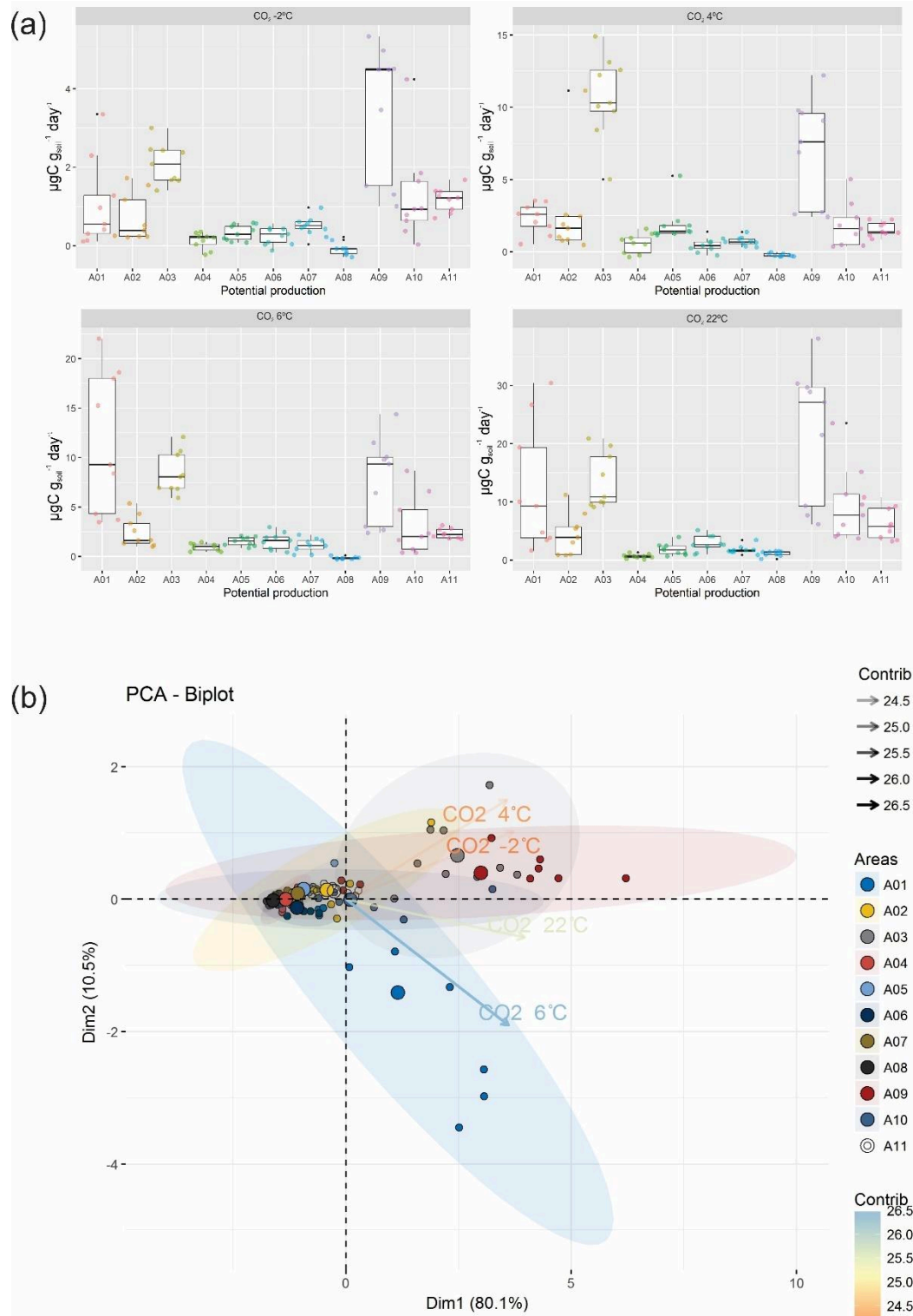


Figure 4. Average values of CO₂ production potential at -2, 4, 6, and 22 °C, in 11 areas sampled along a toposequence (a); Principal component analyses – PCA indicating discrimination and grouping of plant communities according to the CO₂ soil production values, at temperatures of -2 °C, 4 °C, 6 °C, and 22 °C (b).

The first axis of PCA explained 80.1 % of variance and was positively correlated with 22 °C ($r = 0.95$; $p < 0.05$) (Figure 4b). Despite an overlap of most areas, there is a grouping between area 1 and 6 °C temperature conditions (Figure 4b), explained because of the greatest

sensitivity of CO_2 at 6 °C (Table VI), with an increase of $10.4 \text{ ugC g}_{\text{soil}}^{-1} \text{ day}^{-1}$. Areas 3 and 9, although different in plant composition and landscape position, were grouped with CO_2 at -2 and 4 °C. In Figure 5d they are grouped due to their N, MO and clay values. High production potential was expected in area 5, due to the mixed and abundant plant composition on an uplifted marine terrace, composed with areas with more scattered vegetation, such as area 9. However, this area showed CO_2 production potential close to the Moss Carpet with lower species diversity (area 7).

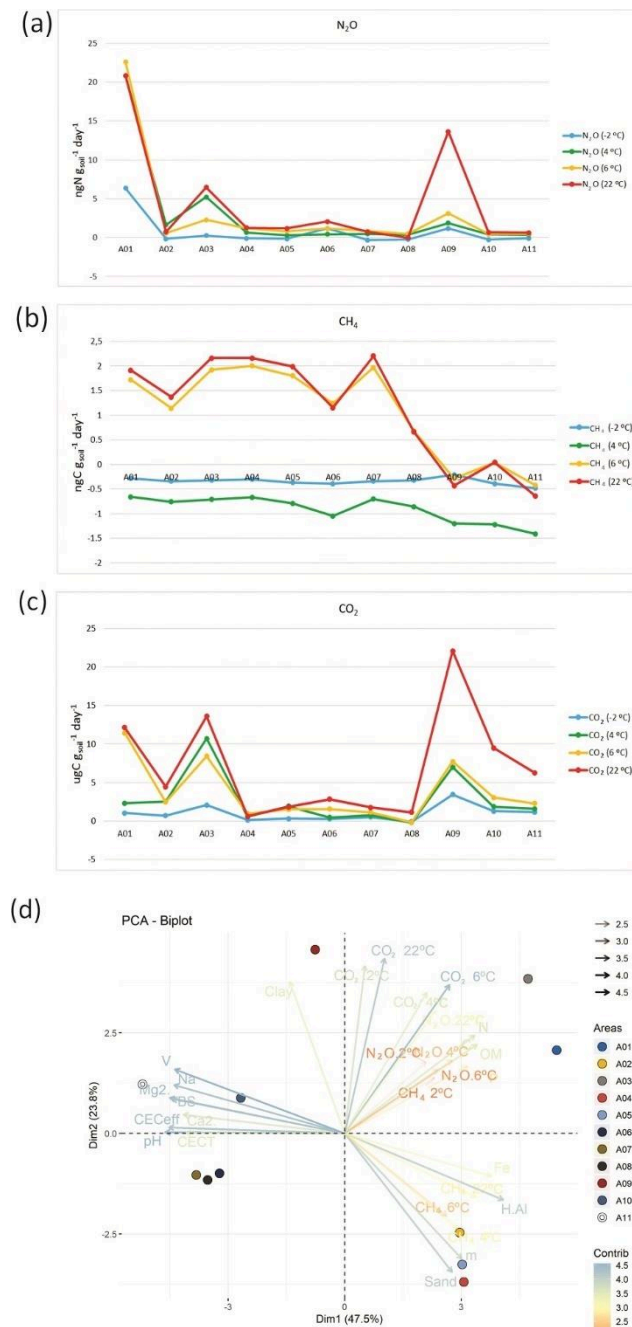


Figure 5. a) N_2O , b) CH_4 , c) CO_2 soil production values, at temperatures of -2 °C, 4 °C, 6 °C, and 22 °C for 11 areas analyzed, and d) PCA for main soil properties and GHG potential production.

4. DISCUSSION

The potential of greenhouse gas emissions in maritime Antarctica ecosystems showed a positive correlation with increasing temperature across this toposequence, demonstrating that more GHG will be released in a warming scenario. GHG emissions exhibited spatial variations related to the vegetation type. The interplay between floristic composition, plant species diversity, and chemical and physical soil attributes influenced the different GHG patterns. However, some patterns are apparently related to the vegetation cover. The general GHGs production tended to be similar for the three GHGs where Moss Carpets occur, highlighting a great CO₂ sink potential for the region and a great CH₄ source. On the other hand, Fruticose Lichens Communities showed a CH₄ sink potential. In this study, floristic composition did not significantly affect N₂O and CO₂ sources, whereas lichens and phanerogams tended to act as a source with higher temperatures.

The lower moist community, at area 1, showed N₂O production potential higher than any other areas, even when comparing other Phanerogamic Communities at all temperatures (Figure 2a), but when comparing the soil properties, it groups with area 3 (Figure 5d). These data corroborate the studies by Vieira et al. (2013) at Hennequin Point, Nelson Island, which observed higher N₂O emissions in soils with vegetation and strong bird influence (ornithogenesis). These authors related these values to low pH and soil texture, where the aeration provided by the sandy soils decreases the mineralization rate of N₂O emission when compared with bare soil. The soil chemistry in area 1 (Table III) shows the lowest pH value, negatively grouped to pH in PCA (Figure 5d), resulting from active guano deposition, contributing to enhance microbial activity and nutrient cycling (Schaefer et al. 2008, Simas et al. 2007b, Michel et al. 2006, Tatur 1989).

Vieira et al. (2013) also demonstrated that the absence of vegetation, as in area 8, leads to N₂O sinks even at higher temperatures (0.02 mg N₂O m⁻² h⁻¹ at 22 °C). These authors suggest that since soil total organic C and total N were extremely low, a very N₂O efflux is expected.

Zhu et al. (2014b) observed the N₂O sinks generally occurred at waterlogged areas (-3.0 ± 1.2 µg N₂O m⁻² h⁻¹) where water table is an important driver of GHGs fluxes, while dry and mesic marsh areas presented weak or strong N₂O sources (41.6 µg N₂O m⁻² h⁻¹ and 2.2 µg N₂O m⁻² h⁻¹ respectively). The same pattern occurred in the waterlogged moss carpet in this study (area 7 with -3.0 ngN g_{soil}⁻¹ day⁻¹) (Figure 2b), but we also observed different sink areas

with distinct vegetations (Table II). Therefore, when comparing vegetation cover, there is no relationship with the N₂O sink effect.

The Moss Carpets Communities (areas 4 and 7) experiences distinct soil moisture conditions and both showed the largest CH₄ production potentials (Figure 3a), with no difference between communities (Figure 3b). Area 7 is directly influenced by the active snow melting, while area 4 is located on an uplifted marine terrace, accumulating water from upslope. In these areas the difference in CH₄ rates was expected, since the current anaerobic conditions in area 7 would restrict methanogenic activity (Vieira et al. 2013). Despite the same CH₄ production values, they were not grouped by soil properties. Zhu et al. (2014b) registered a great temporal variation in CH₄ fluxes from tundra areas in maritime Antarctica, where high CH₄ uptake mainly occurred at a relatively dry area ($27.7 \pm 5.0 \mu\text{g CH}_4 \text{ m}^{-2} \text{ h}^{-1}$).

Even considering these Antarctic ecosystems a CH₄ sink at normal local temperatures (-2 °C), with increasing temperatures (4 °C) (Table V), we further detect a CH₄ production potential (warming) including waterlogged areas, with increased sensitivity of CO₂ at 6 and 22 °C (Table VI). The same CH₄ sink ecosystem pattern was found in permafrost in the Arctic (Natali et al. 2015), highlighting the importance of soil moisture conditions by thawing permafrost on the magnitude of C losses, as well as the form of C released.

The highest rates of CH₄ emissions were recorded at 6 °C, however there was a drop in emission when raised to 22 °C (Figure 5b). This pattern can be associated with the activity of different methanogen groups, active at lower temperatures and inactive at higher temperatures. Franzmann et al. (1997) registered methanogens in a lake derived from marine water, East Antarctica, where no growth occurs at temperatures above 19 °C.

The CO₂ sensitivity with the actual influence of animal colonies (area 1) and the CO₂ production potential at 6 °C, indicate significantly higher mean values of the respiration rates in areas influenced by colonies of marine animals, where the deposition of their excrement can have an important effect on the CO₂ exchanges (Zhu et al. 2014a). Increased microbial activity is expected to increase soil organic matter and consequently enhances CO₂ production potential from maritime Antarctic soils (Zdanowski et al. 2005). There is also a temperature range that positively affects bacterial numbers on maritime Antarctica (between ca. 7 and <11 °C), while temperatures outside this range had a negative impact (Zdanowski et al. 2005). Microbial biomass, mineralization process and soil respiration are typically higher in ornithogenic soils (Barrett et al. 2006, Tscherko et al. 2003). The soil microbial diversity results in more intense soil respiration accounting for higher CO₂ production potential in areas

of ornithogenic influence, associated with the highest levels of organic soil carbon (Ma et al. 2014), as seen by Vieira et al. (2013).

On the other hand, this pattern of CO₂ emissions was not restricted to the lower communities of the topography. The PCA (Figure 4b) included an upper area (area 9) and two bottom areas (areas 2 and 3) evidencing the relation with CO₂ production potential (temperatures of -2 °C and 22 °C). Even with a vegetation cover dominated by lichens and sparse mosses (Table SIb), area 9 shows great amount of organic matter (2.87 dag/kg - Table III). Therefore, this was a determining factor for the high CO₂ production potential in the area 9.

This OM influence is also evident when analyzing the area with the highest CO₂ influx (e.g., area 8). Area 8 is predominantly non colonized by plants, with the lowest OM index (0.39 dag/kg - Table III), being the only one that acted as a CO₂ sink in the toposequence (Figure 4a). In general, the presence of vegetation cover favored a higher CO₂ sink strength, notably where cryptogamic communities had low OM contents. Increasing CO₂ values were recorded in Phanerogamic Communities, with greater vegetation cover, greater species richness, and higher rates of soil respiration. Mendonça et al. (2010) recorded mean soil CO₂ emission higher for *D. antarctica* than for *Sanionia uncinata* (Hedw.) Loeske. at King George Island and suggesting that soil temperature is not the main factor controlling these emissions, despite similar soil and climate conditions between both sites analyzed.

Thomazini et al. (2015) showed significantly higher CO₂ production potentials under vegetated soils than non-vegetated, while the N₂O potential did not differ between both areas. The CO₂ production potential, according to by La Scala et al. (2010), was 514% higher in areas with vegetation in comparison with bare soils. However, when comparing plant types and emissions, mosses carpets showed lower CO₂ production potential.

Robinson et al. (2018) showed that can occur great changes in these terrestrial Antarctic vegetation communities, mainly in Antarctic moss communities. The changes in moss species composition probably result from changing microhabitats, with a decreasing moisture trend, in Eastern Antarctic terrestrial biota. Hence, waterlogged areas colonized by mosses are proof to changing plant composition resulting from drainage and lower moisture, by increasing temperature. All these features may alter the future GHG production potential scenario in a complex way since mosses are more responsive to their microclimate and rapid environmental changes are/could occur (Robinson et al. 2018). Royles et al. (2013) suggest that the rapid increase in moss growth and microbial activity observed since the late 1950s in the moss bank

dataset is a consequence of warming temperatures and increased permafrost melting and summer precipitation, enabling higher metabolic rates and longer growing seasons. Martins et al. (2021) suggest that the local warming may significantly affect the Antarctic marine biota, where the organic compounds reflect the occurrence of similar sources of aliphatic hydrocarbons on Admiralty Bay. The terrestrial sources of these biogenic inputs are Antarctic lichens, mosses, and macroalgae due to meltwater runoff and increased abundance of marine producers.

Temperature, CO₂, and water availability are likely to have a synergistic effect on productivity and nutrient cycling, resulting in alterations to the current balance of the nutrient cycle. If photosynthesis and growth rates of Antarctic plants increase, in response to greater water availability and/or warming temperature, the demand for nutrients will follow the same pattern, leading to the development of a nutrient-limited system (Robinson et al. 2003).

This possible scenario of increased temperature and changes in precipitation may also cause drastic responses in the Antarctic ecosystems in relation to the CO₂ flux, since temperature and soil moisture are related to microbial activity and soil organic carbon mineralization (De Souza Carvalho et al. 2013, Bokhorst et al. 2007, Davidson & Janssens 2006, Zdanowski et al. 2005). According to Fischer (1990), moisture and temperature in Arctic soil at +8 to +12 °C affect metabolic process, O₂ consumption and CO₂ production as a function of water availability.

The rate of guano decomposition depends mainly on bacterial activity, which, as most biological processes, also depends on water availability (Zdanowski et al. 2005). Zhu et al. (2014b) evidenced the strong correlation between respiration ecosystem and soil temperature, suggesting that climate warming might decrease CO₂ sink through increasing soil respiration in tundra marsh and upland tundra.

Thus, changes in soil moisture are particularly important as soil attributes are the main environmental drivers of tundra C exchange (Natali et al. 2015, Oberbauer et al. 2007, Shaver et al. 2006, Oechel et al. 1998). These can further enhance permafrost degradation due to water accumulation affecting soil heat flux and thawing process (Natali et al. 2015, Jorgenson et al. 2010, Subin et al. 2013).

This study provides information on GHG emission dynamics based on laboratory incubations combined with field observations detailing the interaction processes between soil and vegetation. Defining GHG emissions patterns from soil and vegetation is an important tool regarding the expected environmental change scenarios. The monitoring of these areas

and data collection/expansion for the Antarctic peninsula is needed due to the ecological importance of polar ecosystems and their sensitivity to climate changes.

5. CONCLUSION

1. This study revealed the potential GHG emissions among different soils coverage and temperature ranges across a toposequence in Antarctica. Furthermore, this work demonstrated that soil and vegetation monitoring is crucial to understand how vegetation communities play an important and sensitive indicator of local climate change, varying in space and time. The increase in soil temperatures is correlated with more GHG emitted to the atmosphere in maritime Antarctica ecosystems.

2. The floristic composition, plant species diversity, and subsequent chemical and physical soil attributes influenced different GHG emissions patterns.

3. Moss Carpets Communities acted as a CO₂ source with lower potential of GHG emissions and act as a CH₄ source, specially under warming conditions.

4. Fruticose Lichens Communities at the higher parts of the toposequence showed a CH₄ sink potential.

5. Areas with greater biological influence presents higher N₂O and CO₂ production potentials, especially due higher N, MO, and low soil pH, increased microbial activity, and sandy texture, resulting in a decrease of N₂O mineralization rate.

6. N₂O and CO₂ exhibited spatial variations between vegetation types, but the presence of soil organic matter was a determining factor for both production potential observed.

7. Bare soil is a N₂O sink even under high temperatures conditions, due to the extremely low total organic C and N backgrounds.

8. Changes on soil temperature and moisture affect plant composition and distribution, enhancing GHG emissions in ice-free areas.

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7. AUTHOR CONTRIBUTIONS

The authors FRF and TA executed the research, processed the data, interpreted the results, and wrote the first version of the manuscript. PAB identified the plant communities in the field. SK conducted the laboratory GHG incubations. SCEGR designed the study, supervised the research, and contributed to the review of the write. All authors approved the submission of this work.

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SUPPLEMENTARY MATERIAL

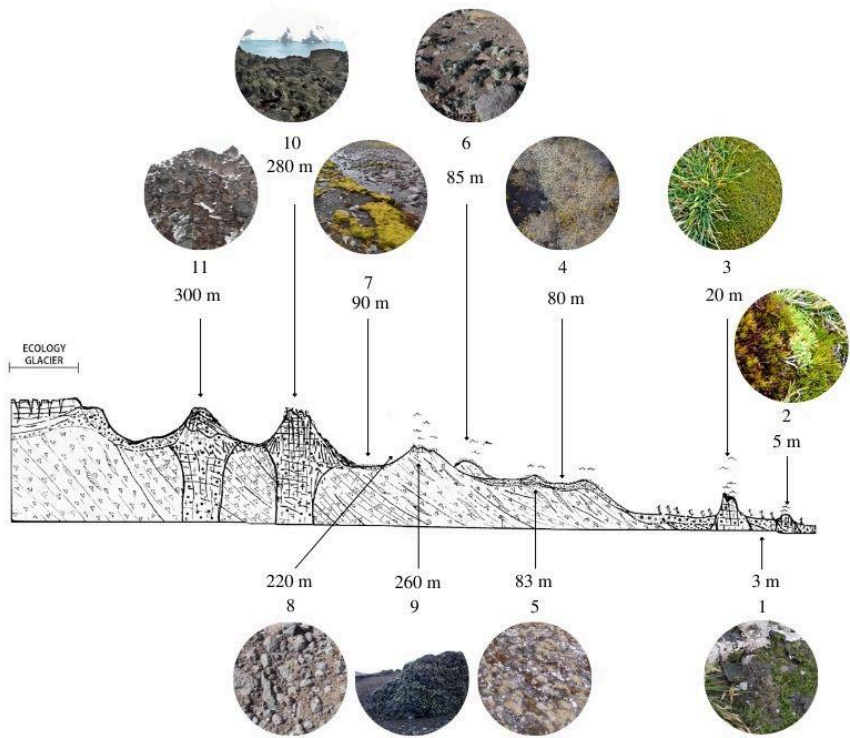


Figure S1. A transect diagram showing the floristic composition and altitude of each area along the toposequence.

Table S1a. Plant and lichen species identified in the 11 ice-free areas.

Group	Family	Specie
Bryophyta	Andreaceaceae	<i>Andreaea gainii</i> Card.
	Amblystegiaceae	<i>Sanionia</i> spp.
	Bryaceae	<i>Bryum pseudotriquetrum</i> (Hedw.) P. Gaertn., B. Mey. & Scherb
	Grimmiaceae	<i>Schistidium antarctici</i> (Card) L.I. Savicz & Smirnova
		<i>Schistidium falcatum</i> (Hook. f. at Wils.) B. Bremer
	Polytrichaceae	<i>Polytrichastrum alpinum</i> Hedw.
	Pottiaceae	<i>Syntrichia magellanica</i> (Mont.) R.H. Zander
Algae	Prasiolaceae	<i>Prasiola crispa</i> (Lightfoot) Menegh.
Phanerogams	Caryophyllaceae	<i>Colobanthus quitensis</i> (Kunth.) Bartl.

Lichenized and lichenicolous fungi	Ochrolechiaceae	<i>Ochrolechia frigida</i> (Sw.) Lyngé
	Parmeliaceae	<i>Himantormia lugubris</i> (Hue) I. M. Lamb <i>Usnea antarctica</i> Du Rietz <i>Usnea aurantiaco-atra</i> (Jacq.) Bory
	Teloschistaceae	<i>Caloplaca regalis</i> (Vainio) Zahlbr <i>Cladonia borealis</i> S. Stenroos

Table SIb. Plant communities grouped according to species with higher index of ecological significance (IES).
F: relative frequency of specie; C: mean specie cover

Area	Community	Species	F	C	IES
1	Phanerogamic	<i>Deschampsia antarctica</i>	100	4.92	591.67
	Community –	<i>Prasiola crispa</i>	41.67	0.50	62.50
	Association	<i>Colobanthus quitensis</i>	25	0.42	35.42
	<i>Deschampsia</i> - <i>Prasiola</i>	<i>Bryum pseudotriquetrum</i>	8.33	0.08	9.03
2		<i>Deschampsia antarctica</i>	100	2.83	383.33
	Phanerogamic	<i>Colobanthus quitensis</i>	91.67	1.42	221.53
	Community –	<i>Politrichastrum alpinum</i>	66.67	1.33	155.56
	Association	<i>Sanionia</i> spp.	50	0.92	95.83
	<i>Deschampsia</i> -	<i>Syntrichia magellanica</i>	25	0.42	35.42
	<i>Colobanthus</i>	<i>Cladonia borealis</i>	8.33	0.17	9.72
		<i>Usnea antarctica</i>	8.33	0.08	9.03
3	Phanerogamic	<i>Deschampsia antarctica</i>	100	3.92	491.67
	Community –	<i>Syntrichia magellanica</i>	83.33	1.42	201.39
	Association	<i>Sanionia</i> spp.	58.33	1.08	121.53
	<i>Deschampsia</i> -	<i>Caloplaca regalis</i>	58.33	0.58	92.36
	<i>Syntrichia</i>	<i>Colobanthus quitensis</i>	16.67	0.33	22.22
		<i>Prasiola crispa</i>	8.33	0.08	9.03
4	Moss Carpet Community	<i>Sanionia</i> spp.	100	4.33	533.33
	– Association <i>Sanionia</i> –	<i>Bryum pseudotriquetrum</i>	50	0.67	83.33
	<i>Bryum</i>	<i>Syntrichia princeps</i>	25	0.42	35.42
		<i>Politrichastrum alpinum</i>	16.67	0.25	20.83
		<i>Deschampsia antarctica</i>	100	3	400
5		<i>Sanionia</i> spp.	75	1.67	200
	Phanerogamic	<i>Politrichastrum alpinum</i>	58.33	0.83	106.94
	Community –	<i>Colobanthus quitensis</i>	58.33	0.58	92.36
	Association	<i>Ochrolechia frigida</i>	41.67	0.58	65.97
	<i>Deschampsia</i> – <i>Sanionia</i>	<i>Usnea antarctica</i>	33.33	0.50	50
		<i>Syntrichia magellanica</i>	8.33	0.17	9.72
		<i>Cladonia borealis</i>	8.33	0.08	9.03
6	Fruticose Lichens	<i>Usnea antarctica</i>	100	2.67	366.67
	Community –	<i>Usnea aurantiaco-atra</i>	41.67	0.92	79.86
	Association <i>Usnea</i> –	<i>Andreaea gainii</i>	41.67	0.83	76.39

	<i>Andreaea</i>	<i>Colobanthus quitensis</i>	33.33	0.33	44.44
		<i>Deschampsia antarctica</i>	25	0.33	33.33
		<i>Syntrichia magellanica</i>	16.67	0.33	22.22
		<i>Ochrolechia frigida</i>	8.33	0.08	9.03
7	Moss Carpet Community – Association <i>Sanionia</i> - <i>Bryum</i>	<i>Sanionia</i> spp.	100	4.83	583.33
8	Bare soil	-	-	-	-
9	Fruticose Lichens Community – Association <i>Usnea</i> – <i>Schistidium</i>	<i>Usnea aurantiaco-atra</i>	83.33	2.33	277.78
		<i>Usnea antarctica</i>	91.66	1.91	267.36
		<i>Schistidium falcatum</i>	41.66	0.75	72.92
		<i>Syntrichia magellanica</i>	33.33	0.66	55.56
		<i>Ochrolechia frigida</i>	33.33	0.58	52.78
10	Fruticose Lichens Community – Association <i>Himantornia</i> - <i>Usnea</i>	<i>Himantornia lugubris</i>	100	2.08	308.33
		<i>Usnea aurantiaco-atra</i>	83.33	2	250.00
		<i>Usnea antarctica</i>	66.66	1.33	155.56
		<i>Andreae gainii</i>	16.66	0.16	19.44
11	Fruticose Lichens Community – Association <i>Usnea</i> - <i>Schistidium</i>	<i>Usnea aurantiaco-atra</i>	91.66	2.33	305.56
		<i>Usnea antarctica</i>	91.66	1.91	267.36
		<i>Schistidium antarctici</i>	58.33	0.83	106.94
		<i>Ochrolechia frigida</i>	8.33	0.08	9.03

Table SIc. Values of carbon dioxide equivalent (CO₂e) for N₂O and CH₄ in ng unit.

Area	N ₂ O – CO ₂ e				CH ₄ - CO ₂ e			
	-2 °C	4 °C	6 °C	22 °C	-2 °C	4 °C	6 °C	22 °C
1	1.90e ⁺¹⁵	6.22e ⁺¹⁵	6.73e ⁺¹⁵	6.20e ⁺¹⁵	-7e ⁻¹⁵	-9.5e ⁻¹⁵	5.95e ⁻¹⁴	4.75e ⁻¹⁵
2	-4.77e ⁺¹³	4.92e ⁺¹⁴	1.73e ⁺¹⁴	2.21e ⁺¹⁴	-8.5e ⁻¹⁵	-1.05e ⁻¹⁴	4.75e ⁻¹⁴	5.75e ⁻¹⁵
3	8.34e ⁺¹³	1.56e ⁺¹⁵	6.82e ⁺¹⁴	1.93e ⁺¹⁵	-8e ⁻¹⁵	-9.75e ⁻¹⁵	6.575e ⁻¹⁴	6e ⁻¹⁵
4	-2.68e ⁺¹³	1.94e ⁺¹⁴	3.58e ⁺¹⁴	3.78e ⁺¹⁴	-7.5e ⁻¹⁵	-9.25e ⁻¹⁵	6.675e ⁻¹⁴	4e ⁻¹⁵
5	-4.77e ⁺¹³	8.64e ⁺¹³	2.47e ⁺¹⁴	3.52e ⁺¹⁴	-9.25e ⁻¹⁵	-1.05e ⁻¹⁴	6.475e ⁻¹⁴	4.75e ⁻¹⁵
6	3.49e ⁺¹⁴	1.28e ⁺¹⁴	3.52e ⁺¹⁴	6.20e ⁺¹⁴	-9.75e ⁻¹⁵	-1.65e ⁻¹⁴	5.725e ⁻¹⁴	-2.25e ⁻¹⁵
7	-8.94e ⁺¹³	1.43e ⁺¹⁴	2.53e ⁺¹⁴	2.18e ⁺¹⁴	-8.5e ⁻¹⁵	-9e ⁻¹⁵	6.675e ⁻¹⁴	5.75e ⁻¹⁵
8	-6.85e ⁺¹³	1.13e ⁺¹⁴	1.46e ⁺¹⁴	-5.96e ⁺¹²	-8e ⁻¹⁵	-1.35e ⁻¹⁴	3.85e ⁻¹⁴	-5e ⁻¹⁶
9	3.49e ⁺¹⁴	5.60e ⁺¹⁴	9.33e ⁺¹⁴	4.07e ⁺¹⁵	-5.25e ⁻¹⁵	-2.475e ⁻¹⁴	2.3e ⁻¹⁴	-3.75e ⁻¹⁵
10	-7.45e ⁺¹³	1.28e ⁺¹⁴	1.37e ⁺¹⁴	2.06e ⁺¹⁴	-9.75e ⁻¹⁵	-2.075e ⁻¹⁴	3.15e ⁻¹⁴	0
11	-2.68e ⁺¹³	1.13e ⁺¹⁴	1.46e ⁺¹⁴	1.88e ⁺¹⁴	-1.2e ⁻¹⁴	-2.325e ⁻¹⁴	2.475e ⁻¹⁴	-5.5e ⁻¹⁵

CAPÍTULO II:

Net ecosystem exchange of CO₂ and interplays with soil, microbial composition and vegetation at maritime Antarctica

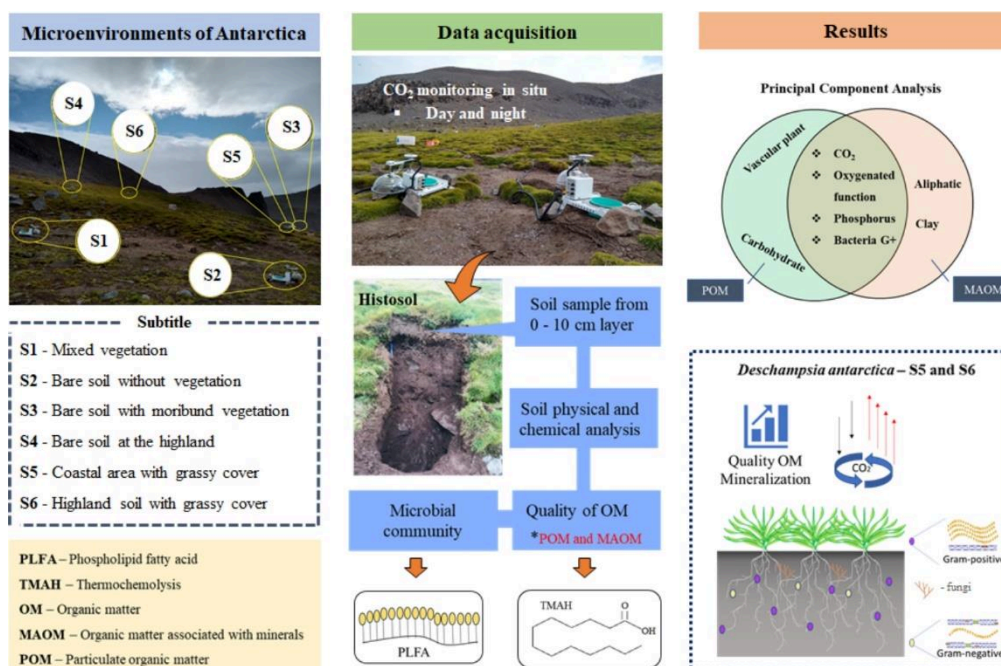
ABSTRACT

FERRARI, Flávia, D.Sc., Universidade Federal de Viçosa, May, 2022. **Net ecosystem exchange of CO₂ and interplays with soil, microbial composition and vegetation at maritime Antarctica.** Adviser: Carlos Ernesto Gonçalves Reynaud Schaefer. Co-adviser: Marcio Rocha Francelino and Jair Putzke.

Antarctic soils are key indicators of climatic changes due to seasonal thawing, organic matter decomposition, and greenhouse gases emissions, closely related to the different vegetation types. Mosses, algae, and lichens produce carbohydrates stimulating microbial activity with high availability of organic compounds for microbial degradation. Higher plants and bare soils present high mineralization processes combined with higher soil temperature regimes. Thus, the objectives of this work were to (i) evaluate the net ecosystem CO₂ exchange, (ii) analyze the microbial community, and (iii) characterize the compounds of organic matter in different vegetation cover and soilscape: site 1: mixed vegetation; site 2: bare soil without vegetation; site 3: bare soil with moribund vegetation; site 4: bare soil at the highland; site 5: coastal area with grassy cover; and site 6: highland soil with grassy cover. CO₂ was measured through a clear chamber system. Soils were characterized by general properties, microbial community, and organic compounds. Net ecosystem exchange of CO₂ in these environmental exhibits variation between sites and plant covers, microbial community, and phosphorus availability. Site 3 showed higher CO₂ emissions (133.81 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) due to organic matter deposited, soil microbial diversity, and the lack of current vegetation. Only the most advanced mixed community showed a carbon sink potential (- 101.77 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), coupled with greater aromatic compounds, lower oxygenated function, and less microbial biomass. Antarctic grassy vegetation emitted 50 to 129 times higher CO₂ than the mixed vegetation due to the abundance of carbohydrates, oxygenated function, nitrogen compounds, and phosphorus. The future CO₂ dynamics of plant communities in Antarctica will show a varying response to environmental changes depending on plant composition, soils, fungi, and Gram-positive bacteria. Also, the greater complexity of plant communities, as a biodiversity indicator, helps promote greater C sink potential.

Keywords: Antarctic vegetation. Soil-plant relationship. Mineralization of organic matter. Microbial communities. Thermochemolysis. Soil respiration.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The Antarctic geosystems amplify signs of environmental changes in their ice-free areas. They are composed of extremely specialized organisms that respond quickly to small environmental variations (Turner et al. 2005). The relationship between the environment and plant growth form materializes clearly in Antarctic vegetation (Longton 1979; Durán et al. 2021). The Antarctic flora is almost entirely limited to cryptogamic species, experiencing extreme growing conditions of low temperatures, harsh winters, continuous summer light, and strong winds (Putzke and Pereira 2001; Robinson et al. 2003; Pereira et al. 2013). Such conditions lead to a high degree of fidelity between the geoenvironment and the particular plant communities, being restricted to a few species (Longton 1979; Schaefer et al. 2007; Poelking et al. 2015), and these factors are strongly modified by topography and microtopography which thus exert major indirect control over local distribution patterns (Longton 1988).

This complex chain of interactions, typical of the Antarctic ecosystem, makes unique Antarctic Cryosols valuable indicators of climatic changes in periglacial environments (Guglielmin et al. 2008; Rodrigues et al. 2019; 2021). Permafrost covers approximately 15% of the global landmass (Zhang et al. 2008), containing 30% of soil organic carbon (SOC), down to 100 cm (Tarnocai 2006; Ping et al. 2015). In addition, such areas are the most

susceptible to global climate change and are expected to suffer the greatest impact on the ecological processes following permafrost degradation (Kettles and Tarno 1999). Unbalanced Cryosols have the potential to thaw, exposing organic matter accumulated over long periods to mineralization and release of greenhouse gases into the atmosphere (Tarnocai et al. 2009; Ping et al. 2015), and how the environment acts in this process can be measured by the net ecosystem emissions of CO₂ (NEE). The quality of soil organic matter (SOM) and the microbial community are factors that control the processes of their accumulation and conservation, allowing inferences on the native and dynamics of terrestrial carbon cycles.

The retreat of glaciers, in recent times, raising soil temperatures coupled with increasing water availability in the active layer favor greater microbial activity, and promote changes in soil attributes, favoring the establishment and succession of vegetation in ice-free areas (Thomazini et al. 2014). Higher plant biomass would not just enhance root respiration but also the spatial distribution of soil CO₂ emissions (Luo et al. 2001; Convey 2005; Tang and Baldocchi 2005; Thomazini et al. 2014). Vegetation patches and soil types are, therefore, two key components in determining nutrient dynamics in Antarctica, especially for the carbon cycle (Thomazini et al. 2014).

Simas et al. (2007b) demonstrated that sites with flowering plants coincide with higher organic C levels, and the total organic levels (TOC) were highest for poorly drained sites where moss peats have formed. This increases the potential of the soils in maritime Antarctic to act as a sink of atmospheric C. Vieira et al. (2013) show that vegetation associated with flying birds had the largest CH₄ influx rates in maritime Antarctica. However, this was counterbalanced by the greatest N₂O efflux rates from these soils, resulting in higher release of greenhouse gases. Zhu et al. (2014) emphasize that the tundra net CO₂ sink strength will decrease by about 50% with marine animal activity and current climate warming. Higher soil organic carbon contents may provide support for a more abundant soil bacterial component, resulting in more intensive soil respiration responsible for higher CO₂ emissions from penguin colony sites (Ma et al., 2013; Zhu et al., 2014).

Antarctic soil microbial investigations have data that fairly indicate active populations although actual numbers and biomass are low in comparison with temperate environments. Despite extreme conditions, a range of microbial ecosystems is found (Beyer et al. 1999; Rosa et al. 2019). Bacteria are the dominant microorganisms and show high metabolic rates (Beyer et al. 1999). Mosses, algae, and lichens produce carbohydrates, which leach into the underlying soil, and these organics may stimulate microbial activity because of the high

availability of the organic compounds for microbial degradation (Bölter 2011). Higher plants and sites without vegetation cover presented higher mineralization processes combined with elevated soil temperature and absence of vegetation cover (Thomazini et al. 2014; 2016).

Despite the importance of Antarctic soil in the global carbon cycle little is known about the CO₂ variability in these unique soils under different vegetation covers. To fill this gap, the objective of the present study was to (i) evaluate the sink and source capacity of the net ecosystem flux of CO₂ in different soil and vegetation covers, through respiration, (ii) analyze the microbial community, and (iii) characterize the organic matter composition to identify the potential of different vegetation in mediating climate changes in ice-free areas of maritime Antarctica.

2. MATERIALS AND METHODS

2.1 STUDY AREA

The study was carried out in ice-free areas in the vicinity of Demay Point, on the Western shore of Admiralty Bay, King George Island, the largest island of the South Shetland Islands archipelago (Fig. 1). The area is delimited by the Baranowski Glacier to the North and by the Windy Glacier to the South and is located within the Antarctic Specially Protected Area number 128 (ASPA 128), where a Polish refuge (62°13'2.9"S, 58°26'32.27"W) serves as a base for ecological monitoring. The area is designated to provide appropriate protection for Antarctic birds, marine mammals, and vegetation, covering about 17 km². The mean annual temperature and relative air humidity during 2013-2017, in Arctowski Station, near the study area, were -1.7 °C and 78.1%, respectively, and the mean annual precipitation in 2017 was 499.8 mm (Plenzler et al. 2019).

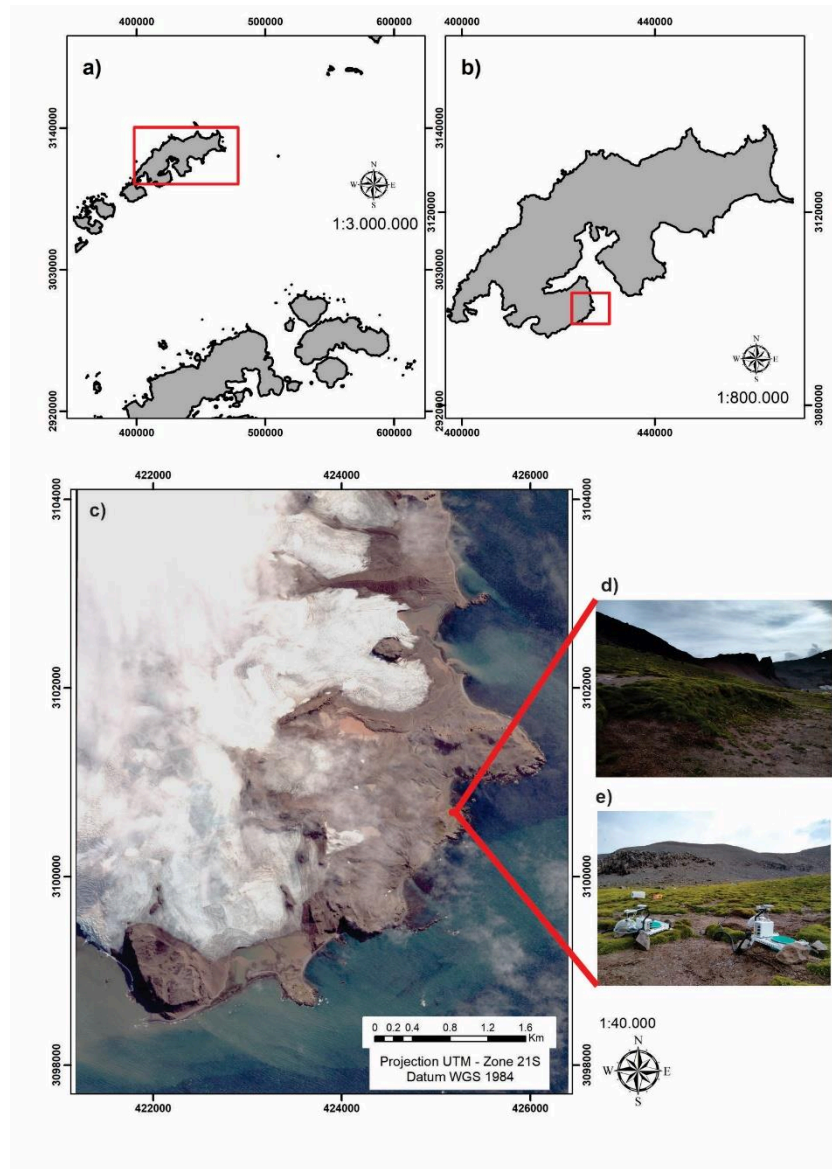


Fig. 1. a) South Shetlands Archipelago; b) King George Island; c) studied area in Demay Point; d) vegetation cover and topography of the landscape studied; e) site of CO₂ chambers; and f) the Histosol Fibrists soil profile.

2.2. SITE CHARACTERIZATION

2.2.1 INVESTIGATED SITE AND CO₂ SYSTEM ESTABLISHMENT

The system of CO₂ emissions evaluation was established considering the floristic composition, soil cover, and position (Fig. 1d, 2). This landscape represents a slope with a large accumulation of organic material deposited, mainly by traces of mosses, and a coastal area with fauna influence, due to the proximity to the elephant seal rest. Currently, the grass *Deschampsia antarctica* Desv. describes the plant community as “Phanerogamic Community” due to their extensive cover plant. Large and scattered rocks occur along the slope. Pereira et al. (2010) described this landscape as a “Moss hummock formation”, with higher biodiversity

of mosses associated with flowering plants, encompassing areas adjacent to the experiment. In this landscape, six sites were selected for the installation of the CO₂ chambers.

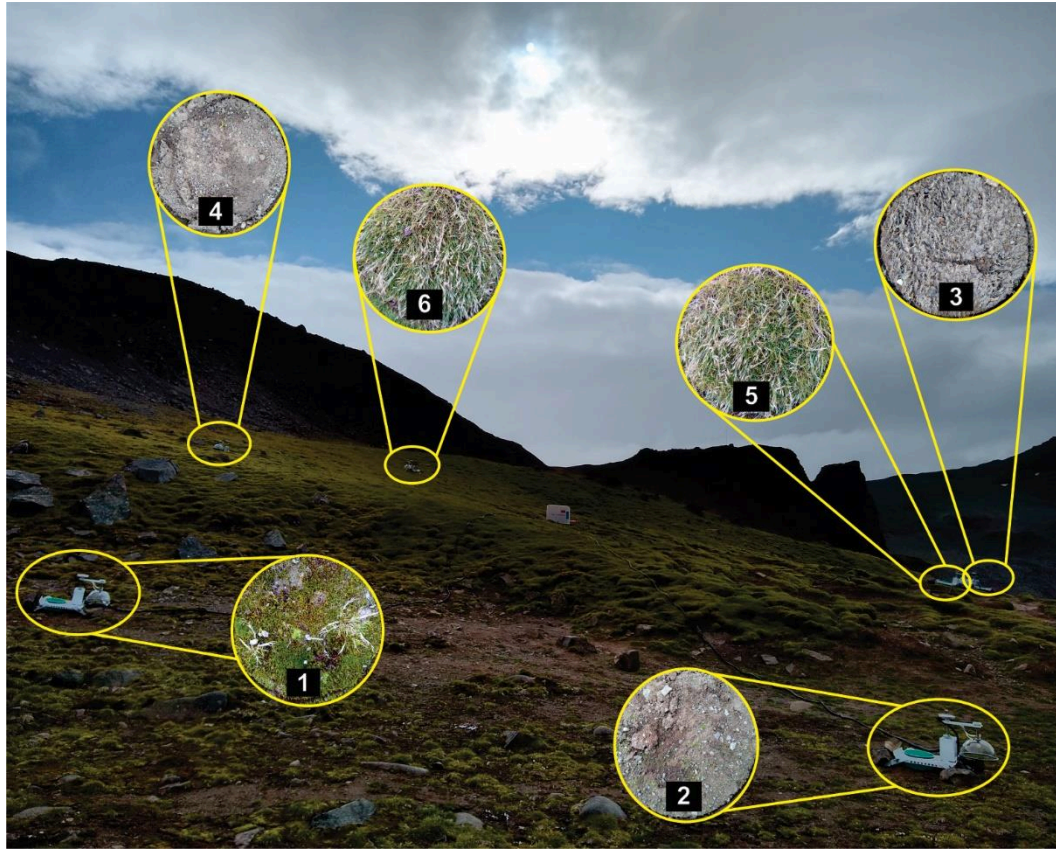


Fig. 2. Site selected containing different characteristics – plant cover and landscape position – showing the CO₂ chambers system and the six sites with specific soil covers. 1: Mixed vegetation; 2: Bare soil without vegetation; 3: Bare soil with moribund vegetation; 4: Bare soil at the highland; 5: Coastal area with grassy cover; 6: Highland soil with grassy cover.

2.2.2 SITE 1 (S1) - MIXED VEGETATION:

Based on the floristic composition and vegetation dominance cover, the plant community in this site was denominated “Phanerogamic-moss carpet community”. Localized at the bottom of the landscape, it presents well-developed mixed vegetation composed of the moss *Polytrichastrum alpinum* Hedw. (Polytrichaceae), which is ornithocoprophilic and can occur in primary areas near the bird colonies, the two native species of vascular plants, with sparse turfs of grass *D. antarctica* (Poaceae) and rarely cushions of *Colobanthus quitensis* (Kurth) Bartl. (Caryophyllaceae), and the moss that represents the major Antarctic biomass, *Sanionia uncinata* Loeske (Amblystegiaceae), growing between the *P. alpinum* tufts. The presence of mosses and the position in the landscape suggest poorly drained soils when compared to the upper position.

2.2.3 SITE 2 (S2) - BARE SOIL WITHOUT VEGETATION:

Localized at the coastal region of the landscape, where marine animals rest providing intense trampling that prevents vegetation growth. In this site, there is no visible organic matter accumulation which represents a contrast to the non-vegetated areas on the slope;

2.2.4 SITE 3 (S3) – BARE SOIL WITH MORIBUND VEGETATION:

There is no current vegetation cover in this site, but a 40 cm depth organic horizon from the moribund deposited vegetation and little stones. The landscape position of this site is at the base of the slope and next to site 5;

2.2.5 SITE 4 (S4) - BARE SOIL AT THE HIGHLAND:

This site is at the highest position on the slope and has no visible deposition and accumulation of organic matter from moribund vegetation due to their inclination on the landscape;

2.2.6 Site 5 (S5) – Coastal area with grassy cover:

This site is localized at the base of the slope and the vegetation is widely composed of *D. antarctica* above the large and visible organic matter deposit;

2.2.7 SITE 6 (S6) – HIGHLAND SOIL WITH GRASSY COVER:

In the highest landscape, this site is in the opposite position of site 5, with dense turfs of *D. antarctica* and next to site 4.

2.2.8 SITE SOIL PROFILE DESCRIPTION

The soil profile was located in the mid-slope landscape position, where vegetation is abundant, dominated by grass *D. antarctica* (Fig. 1f). The soil was classified as Histosol (Table 1) with a clear formation in organic-rich soil material, 50 cm deep, and with moss fibers. All soil horizons ranged from strongly acidic to moderately acidic, with pH between 4.5 and 5.6. The profile showed high levels of exchangeable bases and increased with depth, providing a eutrophic character. The organic matter was concentrated at the surface, at 0 to 27 cm, decreasing with depth and varied in the range of 10 to 133 g kg⁻¹, with downward movement. Expressive concentration of OM (29.9 g kg⁻¹) is seen in the middle of the profile (85 to 97 cm), characterizing a buried A horizon (Table 2). All soil horizons in this profile are dark reddish-brown to dark brown (5YR 3/2 - 7.5YR 3/2) and soil textures is sandy clay loam (Table 3). The exception to this was the Bh horizon, which had higher sand content and a

sandy loam texture, and the BC horizon, which has higher silt content and a loamy texture (Table 3).

Table 1. Location, description, and classification of the sampled soil profile in Demay Point, King George Island

Altitude ¹	Geographic position	Description	Plant community	Soil Taxonomy
20 m	425161 3100667 UTM WGS 84 21S	Buried layer in the soil description with evidence of podzolization. Area with intense colonization by <i>Deschampsia antarctica</i> . Coarse material in the buried layer and Histic horizon with 50 cm. Weakly developed structure in the B horizon. Fine and abundant roots up to 40 cm. Moss fragments were observed in the A horizon and buried 2A1.	Phanerogamic community	Histosol Fibrists

¹ Meter above sea level approximated.

Table 2. Chemical analyses of the sampled soil profile in Demay Point, King George Island

Pedon	Depth (cm)	pH H ₂ O	pH KCl	P	K ⁺	Na ⁺	Ca ⁺	Mg ²⁺	Al ³⁺	H+Al	BS	CECeff	CECT	V	m	ISNa	OM	P- Rem	Cu	Mn	Fe	Zn
				mg/dm ³				cmol/dm ³							%		$\frac{g}{kg^{-1}}$	Mg/L	mg/dm ³			
H1	0-27	4.5	3.08	197.9	158	218.9	12.4	7.6	13.9	24.5	21.4	35.3	45.9	46.6	39.4	2.07	13.3	23.8	4	25.4	153.6	2.1
H2	27-44	4.75	3.29	292.6	98	352.8	24.8	14.7	10.4	15.6	41.3	51.8	56.9	72.6	20.2	2.6	2.0	20.5	5.5	65.5	67.7	0
A	44-52	5.1	3.57	187.8	110	344.7	24.8	13.4	5.3	10.8	40	45.3	50.8	78.7	11.8	2.9	3.9	18.1	8.8	34.5	90.7	0
B	52-68	5.45	3.53	279.6	118	300.1	19.3	9.76	12.8	17.1	30.6	43.5	47.7	64.2	29.6	2.7	1.0	14.2	3.9	31.5	86.7	0
BC	68-85	5.64	3.55	322.3	116	283.8	22	10.2	8.3	13.2	33.8	42.2	47	71.9	19.9	2.6	1.0	18.6	4	30.7	75.9	0
2A1	85-97	5.55	3.62	221.9	92	291.9	20.9	8.4	4.9	11.9	30.8	35.7	42.7	72.1	13.9	2.9	2.9	22	6.1	22.7	120.1	0.2
Bh	97-102	5.45	3.62	449.3	98	287.9	16.0	7.46	4.6	10.5	25.0	29.6	35.5	70.4	15.8	3.5	1.6	23.2	4.8	18	191.2	0.7
BC	102- 125	5.52	3.63	363.2	102	296.0	26.1	10.8	5.7	11.8	38.5	44.3	50.3	76.6	13	2.5	1	19.9	4.8	17.2	97.9	0

CR 125-
140+

pH: active acidity (H₂O; KCl); P: phosphorus; K⁺: potassium; Na⁺: sodium; Ca⁺: calcium; Mg⁺: magnesium; Al³⁺: exchangeable aluminum; H+Al: total acidity; BS: bases of sum; CECeff: effective cation exchange capacity; CECT: total cation exchange capacity pH 7; V: saturation of bases; m: aluminum saturation index; ISNa: sodium saturation index; OM: organic matter; P-Rem: remaining phosphorus; Cu: copper; Mn: manganese; Fe: iron; Zn: zinc.

Table 3. Physical properties of the sampled soil profile in Demay Point, King George Island.

Pedon	Depth		Color	Coarse sand	Fine sand	Sand	Silt	Clay	Texture
	cm		dry	kg⁻¹			g		
H1	0-27	7.5YR 3/2	Dark Brown	0.39	0.16	563	209	209	Sandy clay loam
H2	27-44	7.5YR 3/2	Dark Brown	0.32	0.14	466	262	272	Sandy clay loam
A	44-52	5YR 3/2	Dark Reddish Brown	0.32	0.16	484	274	242	Sandy clay loam
B	52-68	7.5YR 3/2	Dark Brown	0.33	0.15	483	274	242	Sandy clay loam
BC	68-85	7.5YR 3/2	Dark Brown	0.36	0.14	508	259	233	Sandy clay loam
2A1	85-97	5YR 3/2	Dark Reddish Brown	0.33	0.17	510	262	228	Sandy clay loam
Bh	97-102	7.5YR 3/2	Dark Brown	0.25	0.34	604	206	189	Sandy loam
BC	102-125	5YR 3/2	Dark Reddish Brown	0.33	0.16	498	282	220	Loam
CR	125-140+								

2.3 SOIL CO₂ FLUXES

Soil CO₂ exchange ($\mu\text{mol m}^{-2}\text{s}^{-1}$) was measured using a LI-8100 portable analyzer (LI-COR Biosciences, Lincoln, NE, USA) containing an infra-red gas analyzer (model LI-8100-104C), a multiplexer system (model LI-8150), and six clear chambers (model LI-8100-104) (Fig. 1e), calibrated at the factory using precision gases (CO₂ gas standards) at controlled temperatures.

This system quantifies the CO₂ concentration through optical absorption spectroscopy. The clear chamber does not interrupt photosynthesis, which enables the determination of the difference between photosynthetic CO₂ absorption by plants and the ecosystem respiration (ER) losses, which represent the net carbon gain or loss measured by a net ecosystem CO₂ exchange (NEE). This exchange is the balance of ecosystem carbon uptake by primary producers (GPP) and ecosystem respiration (ER) losses (autotrophic plus heterotrophic). NEE values may be both positive and negative. Negative values of NEE represent a carbon sink and positive values represent a carbon source. When NEE = 0, the ecosystem is in equilibrium (Thomazini et al. 2014; 2016).

The six PVC soil collars, with 20 cm diameter, were inserted into the same soil depth of 3 cm, and measurements were recorded for 17 days. The CO₂ concentrations inside the chamber were measured every 1 hour with a 1.5 min duration and interval.

2.4 SITES SOIL SAMPLING

In each chamber, soils were sampled at 0–10 cm depth, stored and identified in plastic bags, and further transported to the TERRANTAR laboratory at the Universidade Federal de Viçosa. After drying, the samples were sieved (2 mm mesh) to separate the stony fraction and large pieces of organic material.

2.5 GENERAL SOIL ATTRIBUTES

Soil properties were measured at the soil laboratory, following standard protocols (Teixeira et al. 2017). The pH in water and CaCl were determined using the ratio soil: liquid 1:2.5; potential acidity (H+Al) as extracted with Ca(OAc)₂ 0.5 mol L⁻¹ buffered at pH 7.0 and quantified via titration with NaOH 0.0606 mol L⁻¹. Exchangeable Ca²⁺, Mg²⁺, and Al³⁺ ions were extracted with 1 mol L⁻¹ KCl, and determined via atomic absorption spectroscopy. Na⁺, K⁺, Fe, and Zn were extracted with Mehlich-1 and quantified using flame photometry. The available phosphorus (P) was extracted with Mehlich-1 and quantified using photo

colorimetry. The remaining P (P-rem) was obtained using a sample of air-dried soil containing $0.01 \text{ mol L}^{-1} \text{ CaCl}_2$. 60 mg L^{-1} of P in the soil using an extractor ratio of 1:10. Effective cation exchange capacity (CEC_{eff}) was calculated by determining the sum of cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , and Al^{3+}) whereas the total cation exchange capacity (CECT) was estimated using the sum of bases (BS) and potential acidity. We determined the bases saturation index (V) through the calculation $V\% = 100\text{BS}/\text{CECT}$, and Al saturation index (m) through $m = (\text{Al} \times 100)/\text{CEC}_{\text{eff}}$. The granulometric analysis was performed using the pipette method.

2.6 ANALYSIS OF PHOSPHOLIPID FATTY ACIDS (PLFA)

The characterization of the soil microbial community was carried out by the extraction and analysis of phospholipid fatty acids (PLFA) (Bligh and Dyer 1959; Balser 2002; Fernandes and Chaer 2010). Soil samples from the 0 to 10 cm layer were collected, stored at -20°C and transported to the laboratory. The samples were lyophilized and subsequently passed through a 2 mm mesh sieve. Three grams (3 g) of soil were added to a centrifuge tube with 0.5 ml of distilled water, 1.5 ml of phosphate buffer, 4 ml of chloroform, 8 ml of methanol, and put to stirred for 16 h at 140 rpm. After that, the samples were centrifuged for 12 min (3x) at 2000 rpm and filtered through a Whatman filter. NaCl was added for the separation phase, followed by the extraction with chloroform and drying at 38°C under N_2 flow. In the next step, chloroform and acetone were added and filtered through a silica column. The solution that passed through the filter was discarded, and methanol was added. The latter filtrate was collected and dried at 38°C under N_2 flow. The samples were suspended with 1 ml of methanol: toluene (1: 1 ratio), 1 ml of potassium hydroxide, added to the internal standard (Methyl Nonadecanoate) and taken to a water bath for 15 min. After, the samples were stirred, separating the phases and extracted, added 2 ml of deionized water, 0.3 ml of acetic acid, and 0.5 ml of hexane and stirred. Finally, the hexane was extracted and dried at 38°C under N_2 flow, followed by the addition of hexane and placed in inserts for chromatographic analysis. The compounds were separated and identified by the physicochemical method in a gas chromatograph-mass spectrometer (GC/MS-QP2010SE). The identification of compounds in the GC-MS was adjusted to 85% similarity. The identification of microbial functional groups is listed in Table 4.

Table 4. Phospholipid fatty acids (PLFA) of the soil are categorized into: abbreviated nomenclature of fatty acids/Biomarkers, organism and functional group.

Fatty acid^{1, 2,3}	Organism	Functional group^{4,5}	Reference
10Me-17:0	Actinomycetes	G+	Wang et al. (2015)
10Me-18:0	Actinomycetes	G+	Wang et al. (2015)
10Me 19:0	Actinomycetes	G+	Pan et al. (2021)
14:0	Unspecific biomarker	Unspecific biomarker	Baumert et al. (2018)
15:0	Unspecific biomarker	Unspecific biomarker	Shimizu (2017)
15:1 (n8)	Bacteria unspecific	Unspecific bacteria of G+ e G-	Perry et al. (1979)
16:0	Unspecific biomarker	Unspecific biomarker	Shimizu (2017)
16:1 (n9)	Bacteria unspecific	G-	Kotas et al. (2017)
17:0	Bacteria unspecific	Unspecific bacteria of G+ e G-	Baumert et al. (2018)
17:1 (n10)	<i>Bacillus</i>	G+	Singh et al. (2016)
18:0	Unspecific biomarker	Unspecific biomarker	Baumert et al. (2018)
18:1 (n11)	Bacteria-Microbial stress	G-	Ferré et al. (2012)
18:1 (n13) - (18:0) ²	Unspecific biomarker	Unspecific biomarker	Shimizu (2017)
18:1 (n6) - (18:2n6)	<i>Sporosarcina sp.</i>	G+	Wang et al. (2014)
18:1 (n9)	<i>Arbuscular mycorrhiza</i> - reducing nitrogen compounds	Fungi	Baumert et al. (2018)
18:2 (n9,12)	Ectomycorrhizal fungi	Fungi	Zechmeister-Boltenstern et al. (2011)
20:0	Aquatic plants/ moss	Plant	Sundh et al. (1997)
20:4 (n5,8,11,14)	Algae	Plant	Haewood (1998)

21:0	Algae	Plant	Sundh et al. (1997)
22:0	Aquatic plants/moss	Plant	Sundh et al. (1997)
22:1 (n21)	Zooplankton	Animal	(C22:1) Shimizu (2017)
23:0	Aquatic plants/moss	Plant	Sundh et al. (1997)
24:0	Aquatic plants/moss	Plant	Sundh et al. (1997)
24:1 (n9)	Fish	Animal	Turkkan et al. (2008)
25:0	Vascular plant	Plant	Sundh et al. (1997)
26:0	Vascular plant	Plant	Viso et al. (1993)
27:0	Algae	Plant	Viso et al. (1993)
35:1 (n17)	nd	nd	nd
44:0	Unspecific biomarker	Animal	Soberl et al. (2014)
a14:0	Aerobic bacteria	G+	Pan et al. (2021); Yan et al. (2018)
a16:0	Sulfate-reducing bacteria	G+	Kotas et al. (2017)
a16:1 (n8)	Methanogenic bacteria	G-	Ferré et al. (2012)
cy19:0	Bacteria-Anaerobes	G-	Huang et al. (2011)
i14:0	Aerobic Bacteria	G+	Pan et al. (2021)
i15:0	<i>Bacillus</i>	G+	Pan et al. (2021)
i16:0	Bacteria unspecific	G+	Pan et al. (2021)
i17:0	Bacteria unspecific	G+	Kotas et al. (2017)
i18:1 (n2)	nd	nd	nd
i26:0	nd	nd	nd
i28:0	nd	nd	nd

¹We attribute fatty acids from aquatic plants to moss biomarkers in this study.

^{2,3}modifications of the biomarker by dehydrogenation and hydrogenation (Sargent et al., 1983; Mouhoub et al., 2018).

⁴nd: not determined

⁵G-: gram-negative; G+: gram-positive bacteria

2.7 SOIL ORGANIC MATTER FRACTIONATION AND ORGANIC COMPOUNDS CHARACTERIZATION

To identify the organic matter compounds, soil samples were collected at each CO₂ chamber, at the 0-10 cm layer, and transported in a cold chamber at -20 °C to the laboratory, for drying and analysis. In each sample, 5 g of soil was passed through a 2 mm mesh, dispersed in 15 mL of sodium hexametaphosphate (5 g L⁻¹), and agitated for 15 hours at 140 rpm. After that, the samples were passed through a 0.053 mm sieve, resulting in two soil organic fractions: particulate organic matter (POM, >0.053 mm) and mineral-associated organic matter (MAOM, <0.053 mm). These fractions were dried in an oven at 60 °C, weighed, and passed through a mesh of 0.149 mm (100 mesh) according to Cambardella and Elliott (1992) for analysis.

For the thermochemolysis technique application, 200 mg of POM and 100 mg of MAOM of each sample were weighed, directly in vials (Del Rio et al. 1998; Grasset and Amblès 1998; Chefetz et al. 2000; Shadkani and Helleur 2010; Estournel-Pelardy et al. 2011; Younes and Grasset 2018). The thermochemistry technique required the addition of tetramethylammonium hydroxide pentahydrate (TMAH) to the POM and MAOM samples. Then, the samples were transferred to an evaporator with a temperature of 38 °C and under nitrogen flow. In a muffle furnace, the samples were submitted to a temperature of 300 °C for 30 min. Subsequently, 1 ml (3x) of Dichloromethane (DCM) was added, stirred, extracted DCM with a glass syringe, and filtered through a PTFE syringe filter. 50 µL of internal standard (Methyl Nonadecanoate) was added and transferred to the evaporator at a temperature of 38 °C under nitrogen flow to evaporate.

The samples received 100 µL of DCM and were vortexed (with two additions of 50 µL DCM), and transferred to the insert (conical bottom with spring) contained within the screw vial. Subsequently, the compounds were separated and identified as done in the PLFA samples, with adjustment for 85% similarity of the molecules.

The identification of the molecules and structures of soil chemical compounds was carried out by NIST (National Institute of Standards and Technology) and the NIH (National Library of Medicine). The organic compounds were categorized into functions: oxygenated, nitrogenated, hydrogenated, and hydrogenated/oxygenated; molecular structure: aliphatic, cyclic aliphatic, aromatic; and organic groups: amino acids, lignin derivatives, lipids, carbohydrates, nitrogen compounds (nitrogen-containing compounds that did not fit into the other categories), terpenes, bioactive (antifungal, antibacterial and semi-chemical compounds

in general), biopolymers (structural compounds with cutin, chitin, and cuticle), microbial activity markers (MAM), and others (Deshmukh et al. 2001; Nierop et al. 2001; Frazier et al. 2003; Wang et al. 2011; Jerry et al. 2003; Estournel-Pelardy et al. 2013; De Aquino et al. 2019). The other categories represent compounds not identified or that did not fit into any specific category. In this study, it was admitted that all hydrocarbons with a multiple carbon chain of five belonged to the terpene because it does not contain any organic characteristics/functions of the other compounds (Ruzicka et al., 1953; Eschenmoser et al., 1990).

2.8 DATA ANALYSIS

CO₂ emissions were interpreted based on descriptive statistics (daily mean, hourly mean, minimum, maximum, median, standard derivation, and day sum - the sum of all analyses during the 17 days). The analyses were carried out using R Environment (R Core Team, 2017) using the package “ggplot2” (Hadley, 2015) for illustration.

The results of thermochemolysis organic compounds and phospholipid fatty acids (PLFA) were analyzed by their abundances, expressed in percentage (%). The percentage was established by converting the peak area to percentage, using the formula:

$$\text{Abundance (\%)} = (\text{compound peak area} \times 100) / \text{total peak area} \quad (1)$$

Principal component analysis (PCA) was performed to explore general trends and to evaluate if the sites could be separated according to soil attributes (chemical and physical parameters), organic compounds, microbial community, and CO₂ emission potential. We also calculated Pearson correlations among soil properties and the PCA ordination axes. The packages “FactoMineR” and “factoextra” were used to visualize the output of exploratory multivariate data analyses (Husson et al. 2017).

3. RESULTS

3.1 SOIL PROPERTIES

The general soil attributes of each chamber site are presented in Table 5. Although the area is covered by same soil class (Histosols Fibrists), sites presented differences between the samples assigned to differences in vegetation cover and position in the landscape. The P, Ca⁺, BS, CECeff, CECT, P-Rem, Cu, Mn, and silt values were higher in the upper slope positions (sites 6). Conversely, Na⁺, Al³⁺, H+Al, m, and ISNa contents increased in the lower landscape positions (sites 2, 1, and 3). All sites showed moderately acidic pH values, ranging from 5.1

to 6.1. Site 3 had the highest clay concentration in a sandy clay loam texture, followed by the high sites and decreasing along the slope.

Table 5. Soil properties (0-10 cm) along with the sites on mixed vegetation (S1), bare soil without vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5), highland soil with grassy cover (S6) in Demay Point, maritime Antarctica

Properties	Sites					
	S1	S2	S3	S4	S5	S6
pH H₂O	6.1	5.5	5.1	6.1	5.2	5.6
pH KCl	4	3.6	3.4	4.2	3.7	4.5
P (mg/dm³)	54.6	108.3	105.2	99	114.8	128.6
K⁺ (mg/dm³)	117	180	143	70	160	102
Na⁺ (mg/dm³)	540	710	360	530	400	460
Ca⁺ (cmol/dm³)	22.8	18.8	6.7	35.4	12.9	36.3
Mg²⁺ (cmol/dm³)	13.2	10.4	3.3	11.6	7.1	11.9
Al³⁺ (cmol/dm³)	3.7	10.5	9.4	0.6	5.8	0.4
H+Al (cmol/dm³)	8.2	15.8	16.8	4.2	15.1	3.3
BS (cmol/dm³)	38.7	32.8	12.1	49.5	22.1	50.5
CECeff (cmol/dm³)	42.4	43.3	21.5	50.1	27.9	50.9
CECT (cmol/dm³)	47	48.6	28.9	53.8	37.3	53.8
V (%)	82.4	67.5	41.8	92	59.4	93.9
m (%)	8.7	24.2	43.7	1.2	20.7	0.8
ISNa (%)	5.5	7.1	7.3	4.6	6.2	3.9
OM (g kg⁻¹)	1.75	2.6	7.7	2.5	5.3	2.5
P-Rem (mg/L)	17.4	15.6	17.4	26.9	19.4	29.6
Cu (mg/dm³)	2.5	4.5	3.6	5.3	5	7.4
Mn (mg/dm³)	19.3	34.8	8.5	30.4	22.9	76.5
Fe (mg/dm³)	47.5	111.9	111.7	43.8	121.4	88.7
Zn (mg/dm³)	0.4	0.9	1.7	0.4	1.2	1.3
Sand (g)	520	500	540	410	540	430
Silt (g)	290	350	190	390	300	370

Clay (g)	190	150	270	200	160	200
Texture	Sandy loam	Loam	Sandy clay loam	Loam	Sandy loam	Loam

pH: active acidity; P: phosphorus; K⁺: potassium; Na⁺: sodium; Ca⁺: calcium; Mg: magnesium; Al³⁺: exchangeable aluminum; H+Al: total acidity; BS: bases of sum; CECeff: effective cation exchange capacity; CECT: total cation exchange capacity pH 7; V: saturation of bases; m: aluminum saturation index; ISNa: sodium saturation index; OM: organic matter; P-Rem: remaining phosphorus; Cu: copper; Mn: manganese; Fe: iron; Zn: zinc.

3.2 CO₂ EMISSION

The CO₂ emission rates are presented in Fig. 3a, highlighting a high variability during the day and between the 17 days analyzed, and demonstrating a contrast between sites with vegetation and bare soil.

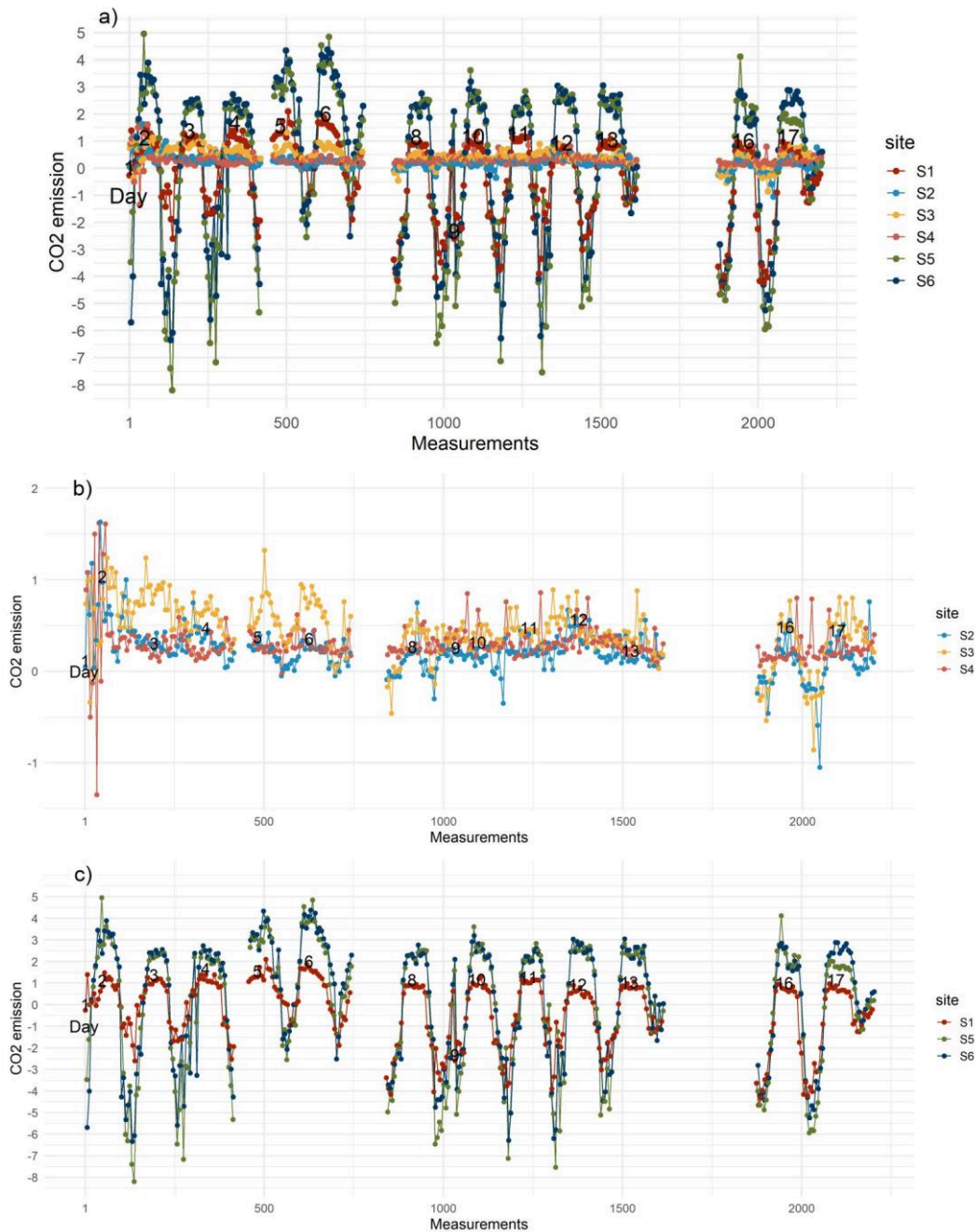


Fig. 3. a) CO₂ emissions measurements from mixed vegetation (S1), bare soil without vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5), highland soil with grassy cover (S6) during 17 days analyzed in Demay Point, maritime Antarctica; b) CO₂ emission in sites without vegetation cover; c) and with vegetation cover.

In Demay Point, only the well-developed mixed vegetation (site 1) acted as a CO₂ sink throughout the NEE measurements (Table 6), when observing the time window of the experiment (17 days). This mixed vegetation resulted in $-101 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ being absorbed at the moment when the source values are compensated for the sink efforts, presenting a negative value means ($-0.33 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

Table 6. Descriptive statistics of net ecosystem CO₂ exchange (NEE - $\mu\text{mol m}^{-2} \text{s}^{-1}$) sites on mixed vegetation (S1), bare soil without vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5), highland soil with grassy cover (S6) in Demay Point, maritime Antarctica

Site	Mean	Standard Derivation	Median	Minimum	Maximum	Days sum ¹
S1	-0.33	1.53	0.16	-4.66	2.10	- 101.77
S2	0.21	0.24	0.2	-1.05	1.63	64.92
S3	0.44	0.3	0.45	-0.86	1.32	133.81
S4	0.29	0.22	0.26	-1.35	1.62	89.68
S5	0.01	2.89	1.01	-8.2	4.96	3.48
S6	0.25	2.69	1.30	-6.34	4.38	75.31

¹Days sum: sum of values analyzed during the 17 days.

Vegetated grassy sites presented large data amplitudes of NEE too (Fig. 3b), in contrast to the greater stability of values in the other sites (Fig. 3a). With source strength of 4.89 and sink capacity of -8.2, site 5 shows a low mean of NEE, practically null ($0.05 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$). While at the high landscape, site 6 ranged between $-6.34 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ and $4.38 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ (Table 6). Overall, both sites showed positive values of CO₂ on the sum of the days, losing 3.48 and 75.31 $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ to the atmosphere, respectively.

The net exchange with higher daily sink capacity in vegetated sites results from the active photosynthetic processes of the vascular vegetation. In the 17 days of measurements, these areas acted as a CO₂ sink in 9 of them (Fig. 3c; 4a). During the nighttime, plant respiration is evident by the positive net exchange of CO₂, reaching a maximum hourly mean value of $2.84 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ in site 6 at 21h, contrasting with $-2.92 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ at 14h. These vegetated sites maintain a sink effect for 11 hours per day (Fig. 4b).

A small contribution to the CO₂ sink effect was observed in the sites without vegetation cover (sites 2, 3, and 4) (Fig. 3b), acting as CO₂ sources on all of the days and hours (Fig. 4a). These bare soils presented more emissions in days sum cumulative even than the vegetated site 5 (Table 6). Site 3, an organic soil without present-day vegetation at the bottom of the landscape, showed the highest CO₂ mean emissions ($0.44 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$). Despite not

having current vegetation cover, this site is located in a large organic deposit, providing the greatest accumulated value of the experiment ($133.81 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$).

The snow cover also influenced the results, decreasing the sink and source effect in all areas. The snowstorm started on the 13th day of sampling at 00:00 a.m. and lasted until the 15th day at 10:00 a.m. (Fig. 4b).

Gaps in the measurements were registered at three different moments (on the 4th, 7th, and 13th to 15th days) (Fig. 3a), derived from technical problems in the equipment due to adverse environmental conditions.

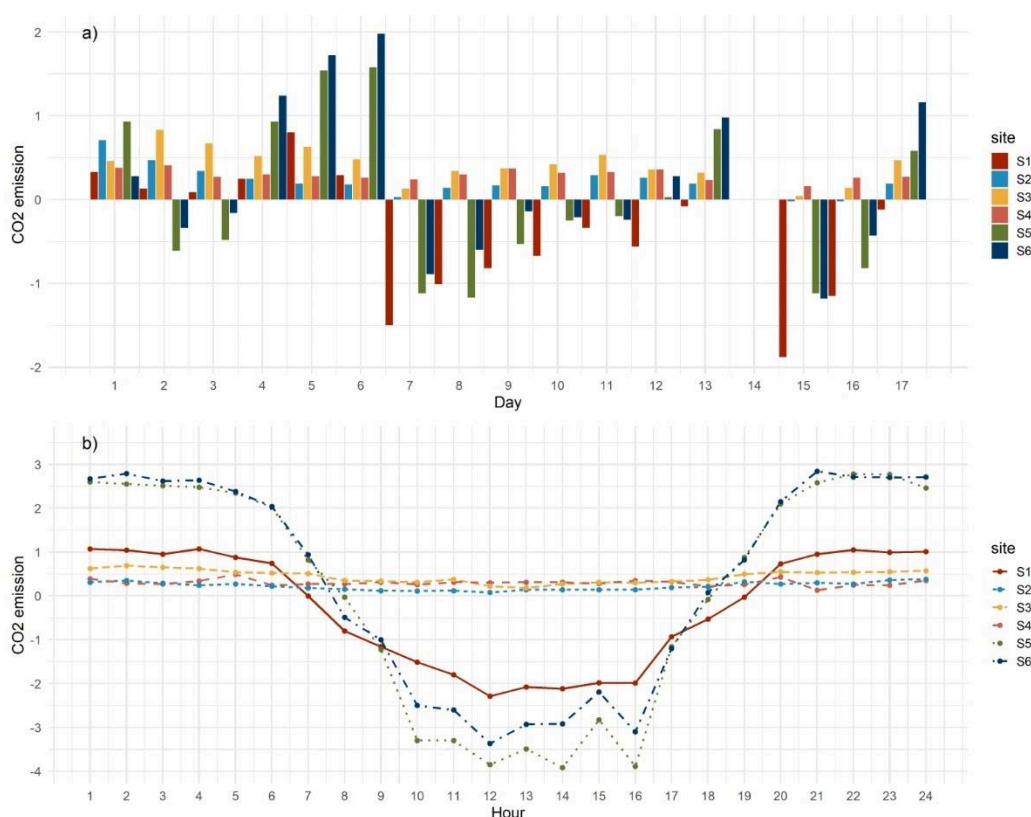


Fig. 4. a) Daily mean of CO₂ emission during the 17 days monitored; b) Hourly mean of CO₂ emission. Mixed vegetation (S1), bare soil with absent vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5), highland soil with grassy cover (S6) in Demay Point, maritime Antarctica.

3.3 MOLECULAR COMPOSITION OF SOIL ORGANIC MATTER FRACTIONS

The results of the thermochemolysis showed that the particulate organic matter compounds (POM) were similar between sites 2 and 4, and sites 3 and 5 (Fig. 5a). Sites 1 and 6 presented different compounds due to the lower lipid abundance, higher bioactive, microbial activity markers, and carbohydrate abundance compared to other sites. The locations occupied by *D. antarctica* (sites 5 and 6) were the only ones to present carbohydrates in the POM, with

site 6 reaching 36%. The bare soil sites (2 and 4) were among the most abundant in lipids (88% and 91.72%).

The organic matter compounds associated with the mineral fraction of organic matter (MAOM) (Fig. 5b) showed a greater distinction among sites when compared to the POM. The microbial activity markers, carbohydrates, lignin derivatives, lipids, amino acids, biopolymers, and bioactive agents are higher in MAOM and/or occurred in all sites (Fig. 6b). The lipids dominated the MAOM from all sites, ranging from 69% to 90%. Bioactive and microbial activity markers (MAM) were more representative in sites 3 (7.29% and 9.28%, respectively) and 5 (7.16% and 12.47%, respectively). These results revealed that, although sites 5 and 6 are covered by the same species, the percentage of compounds was quite divergent, such as bioactive, carbohydrates, MAM, and lignin derivatives with less representation in site 5 and greater in site 6. The vegetated sites (sites 1 and 6), located close to the ends of the organic soil (base and top), presented a percentage of lignin derivatives, MAM, and carbohydrates similar. However, the greater presence of biopolymers and bioactive distinguished site 1 to site 6. At the bare soil site on the top (site 4), there was a higher percentage of microbial markers in MAOM when compared to POM. On the other hand, the bare soil at the base (site 3), maintained a certain similarity between MAOM and POM. Terpene and vitamin did not show a clear pattern of association to sites with and without vegetation, nor with the type of vegetation and CO₂ emissions - being more associated with POM.

The molecular structure of organic compounds revealed that the vast majority of molecules are aliphatic in all sites in both fractions of organic matter (MAOM and POM) representing over 70%, except site 6 in POM (less than 42%) (Fig. 5c). In site 1 there were the highest percentages of aromatic compounds in both MAOM and POM and cyclic aliphatic in MAOM (Fig. 5d). Site 6 showed higher percentages of cyclic and aromatic aliphatic compounds only in POM. The other sites showed cyclic and aromatic aliphatic compounds of less than 6.3% in both fractions of organic matter.

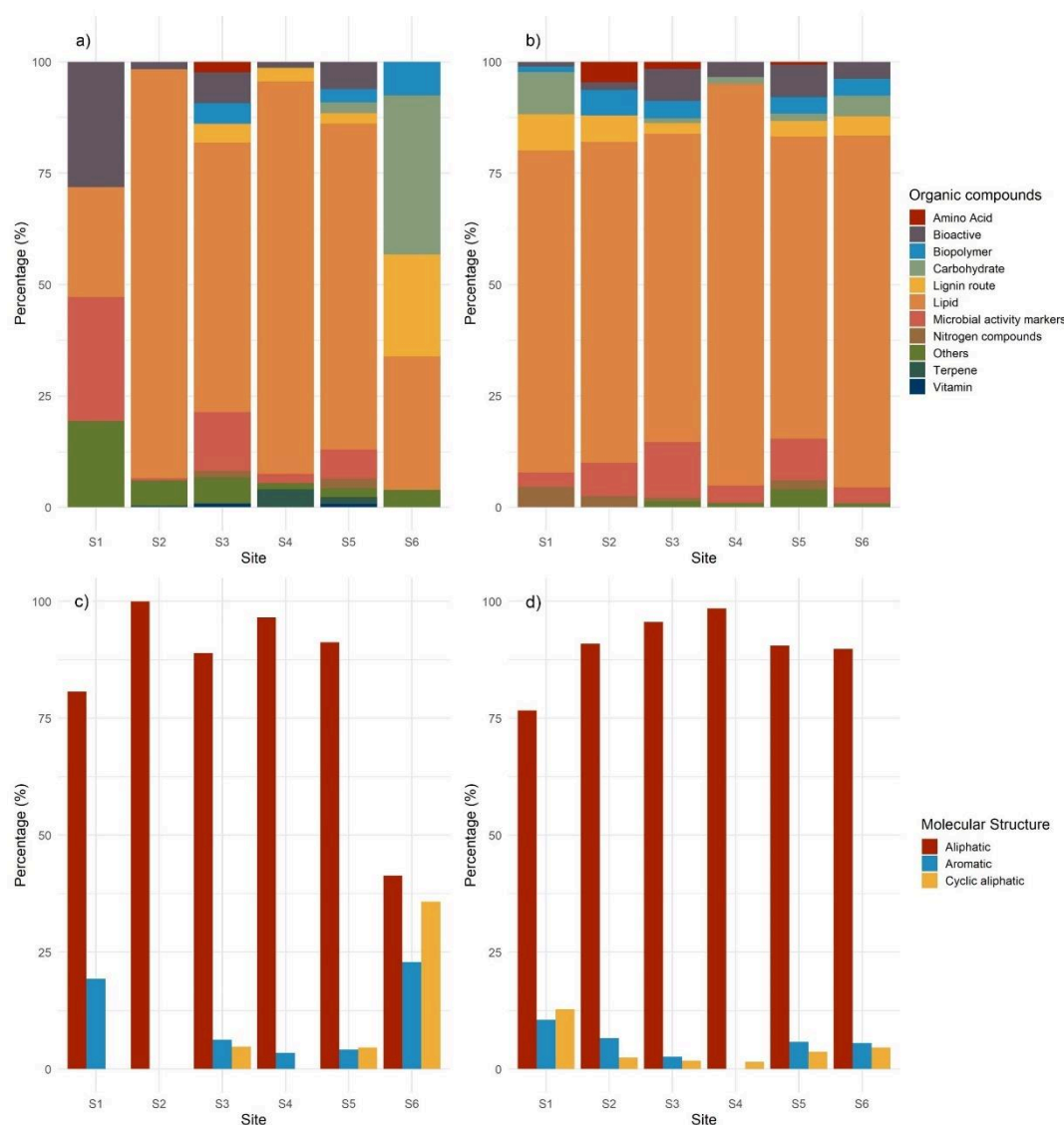


Fig. 5. a-b) The abundance of organic compounds and c-d) the abundance of the molecular structure from particulate (POM) and minerals associated organic matter (MAOM) in sites on mixed vegetation (S1), bare soil without vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5), highland soil with grassy cover (S6) in Demay Point, maritime Antarctica.

The molecular characterization of organic compounds showed that most of the sites had an abundance of oxygenated molecules above 80%, except for the POM in site 1 (less than 50%) (Fig. 6). This site showed a greater balance between the proportions of oxygenated molecules, hydrogenated function, and nitrogenous and oxygenated function, with 43.90%, 28.14%, and 27.95%, respectively. In the other sites, apart from the oxygenated molecules, the molecules had less than 15% of abundance, but there was a higher nitrogenous and oxygenated function category percentage in MAOM.

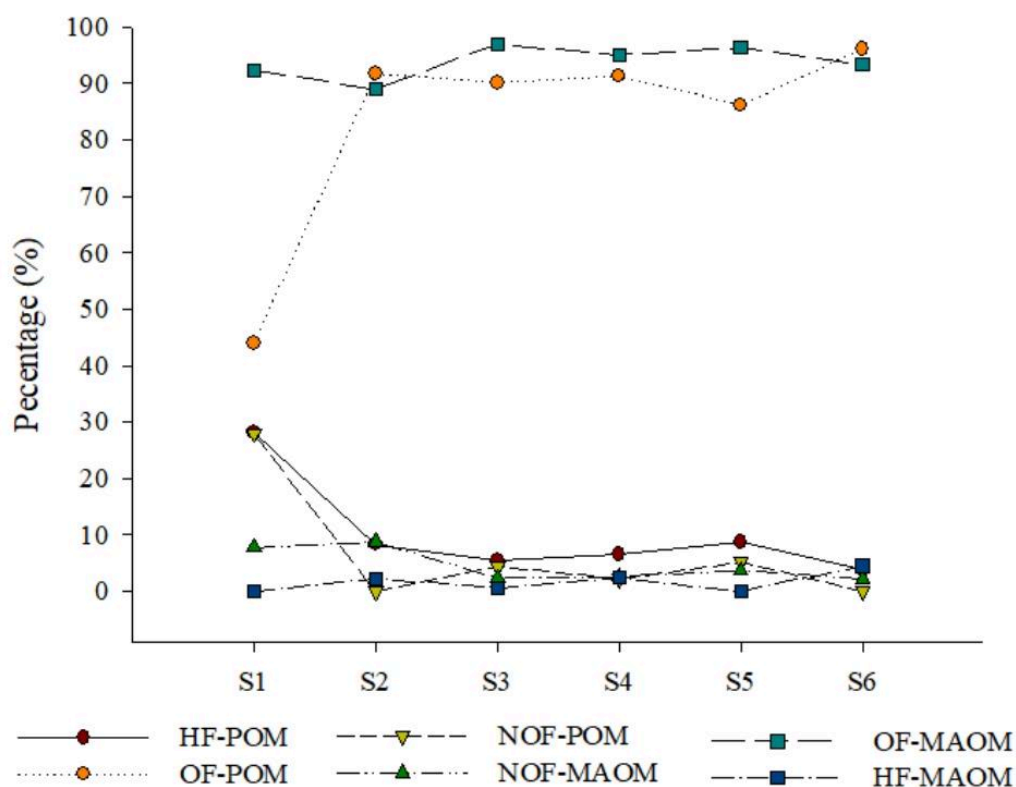


Fig. 6. The abundance of nitrogenous and oxygenated (NOF), oxygenated (OF) and hydrogenated (HF) functions of particulate organic matter (POM) and associated with minerals (MAOM) in sites on mixed vegetation (S1), bare soil without vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5), highland soil with grassy cover (S6) in Demay Point, maritime Antarctica.

3.4 PHOSPHOLIPID FATTY ACIDS (PLFA)

The results of the PLFA analysis showed that 55.61% of the fatty acids are in the highest part of the landscape (sites 4 with 18.73% and 6 with 36.88%) (Fig. 7a). Sites 2 and 3 had the lowest abundance of fatty acids in the coastal region of the landscape, with 7.38% and 10.18% respectively. In the total abundance of PLFA, we identified 42 fatty acids, classified into 16 organisms (Fig. 7b) and 7 functional groups (Fig. 7c).

All sites contained moss markers, with close abundances ranging between 2 and 9% (Fig. 7b). *Arbuscular mycorrhiza* fungi and bacteria unspecific occurred in all sites, but they were more abundant in the highest sites (sites 3, 4, 5, and 6). The higher sites were also more abundant in aerobic bacteria, with an abundance between 15% and 23.5%. Vascular plant markers were only found at sites with higher CO₂ emissions (sites 3, 4, 5, and 6). The *Bacillus* group drew attention due to the abundance at site 3, with 22.86% (Fig. 7b).

We grouped organisms into 7 broader functional groups: G+ bacteria, G- bacteria, nonspecific bacteria, fungi, plants, animals, and unspecific bacteria (Fig. 7c). Plant markers were most abundant at sites 3, 4, 5, and 6 and animal biomarkers were most abundant at sites

1 and 2. The abundance of G- bacteria was low, with 16.9% being the highest value on site 4. Fungi were also present in all sites, however they were more abundant in sites 4 and 5. Sites with higher CO₂ emissions were more abundant in bacteria and G+ (sites 3, 4, 5, and 6), ranging from 19.02% to 45.53 %.

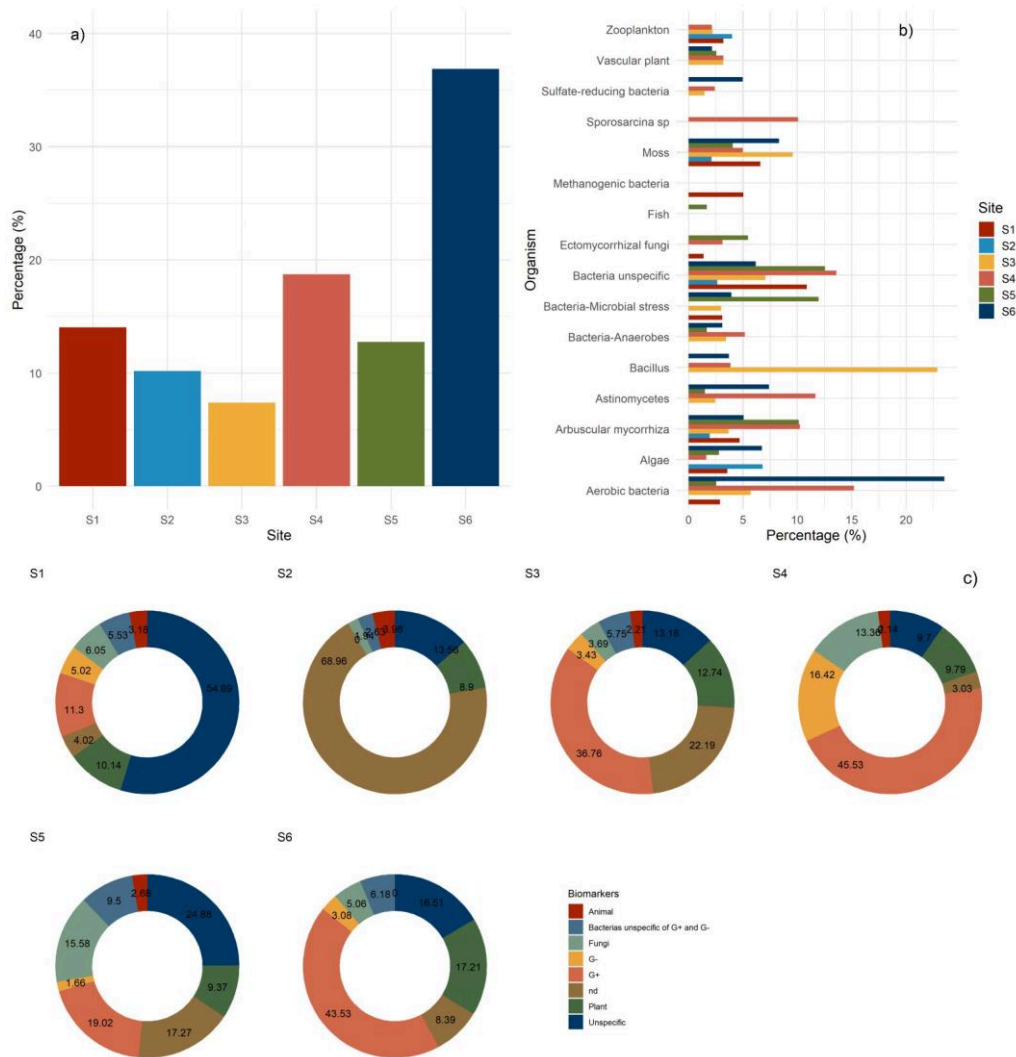


Fig. 7. a) The abundance of phospholipid fatty acids (PLFA), b) the abundance of organisms, and c) The abundance of functional groups (biomarkers) in the sites on mixed vegetation (S1), bare soil without vegetation (S2), bare soil with moribund vegetation (S3), bare soil at the highland (S4), a coastal area with grassy cover (S5) and highland soil with grassy cover (S6) in Demay Point, maritime Antarctica.

3.5 INTEGRATING SOIL AND ORGANIC MATTER PROPERTIES

The principal component analysis (PCA) separated the chemical and physical soil attributes, the microbial groups, the organic matter compounds associated with the mineral fraction (MAOM), and the particulate organic matter (POM) (Fig. 8).

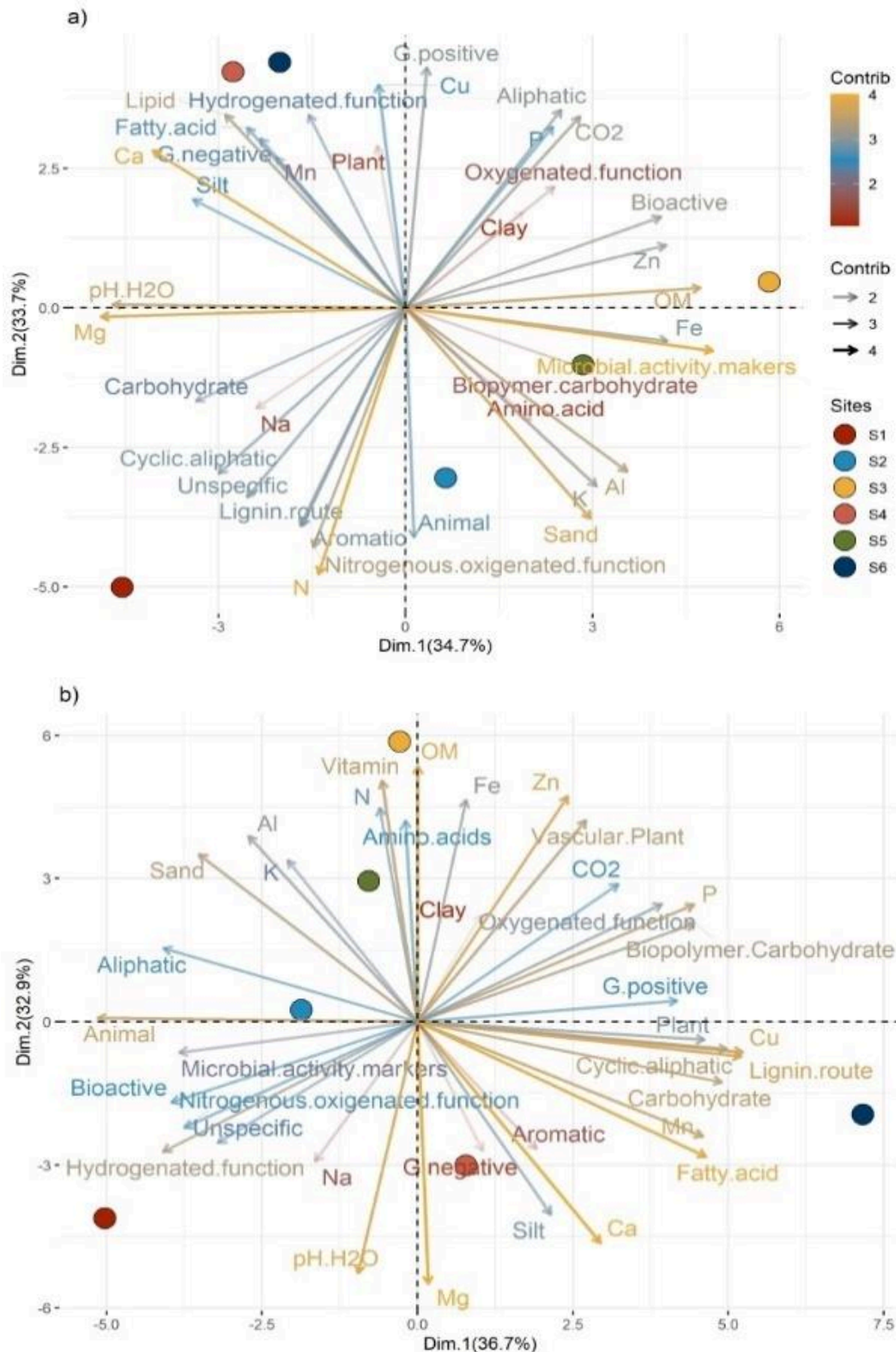


Fig. 8. Principal component analysis - PCA indicates the separation of sites according to the chemical and physical soil attributes in the a) Organic Matter Compounds Associated with the Mineral Fraction, and b) Particulate Organic Matter. pH: active acidity (H₂O), P: phosphorus (mg/dm³), K: potassium (mg/dm³), Na: sodium (extractor Mehlich-1) (mg/dm³), Ca: calcium (cmol/dm³), Mg: magnesium (cmol/dm³), Al³⁺: exchangeable aluminum (extractor KCl 1 mol L⁻¹) (cmol/dm³), OM: organic matter (g kg⁻¹), Cu: copper (mg/dm³), Mn: manganese (mg/dm³), Fe: iron (mg/dm³), Zn: zinc (mg/dm³), Sand, Silt and Clay (g); Average net CO₂ exchanges in the ecosystem - CO₂ (μmol m⁻² s⁻¹); Animal: biomarkers associated with animal; N: Nitrogen compounds, Plant: biomarkers associated with vascular plant. Dim.1 and Dim.2: axis of dimensions.

The first two axes of the PCA related to MAOM (Fig. 8a) explained 68.4% of the variation in the soil data. The first axis explained 34.7% (Dim.1) of variance and was positively correlated with microbial activity makers ($r = 0.98$, $p < 0$), OM ($r = 0.98$, $p < 0.004$), Fe ($r = 0.94$, $p < 0.03$), Zn ($r = 0.83$, $p < 0.03$), bioactive ($r = 0.81$, $p < 0.04$), and negatively correlated with pH H₂O ($r = -0.93$, $p < 0.005$) and Mg ($r = -0.97$, $p < 0.001$). The second axis (Dim.2) explained 33.7% of the variation in soil data and was positively correlated with G+ ($r = 0.85$, $p < 0.02$) and animal ($r = -0.81$, $p < 0.04$), and negatively correlated with nitrogenous and oxygenated function ($r = -0.85$, $p < 0.03$), and N ($r = -0.94$, $p < 0.003$) (Fig. A1; Table A.4).

The second PCA is related to POM (Fig. 8b) and explained by 69.6% by the first two axes. The first axis (Dim.1) explained 36.7% of variance and was positively correlated with Cu ($r = 0.93$, $p < 0.006$), lignin route ($r = 0.92$, $p < 0.007$), cyclic aliphatic ($r = 0.88$, $p < 0.01$), fatty acid ($r = 0.82$, $p < 0.04$), and plant biomarkers ($r = 0.82$, $p < 0.04$), and negatively correlated with animal biomarkers ($r = -0.91$, $p < 0.009$). The second axis (Dim.2) explained 32.9% and was positively correlated with OM ($r = 0.95$, $p < 0.002$), vitamin ($r = 0.90$, $p < 0.01$), Zn ($r = 0.84$, $p < 0.03$), and Fe ($r = 0.82$, $p < 0.04$), and negatively correlated with Mg²⁺ ($r = -0.98$, $p < 0.0005$) (Fig. A.2, Table A.5).

The sites formed some groups in the PCA associated with MAOM (Fig. 8a), where sites 5 and 3 were grouped with Fe, OM, Zn microbial activity markers, bioactive, biopolymer carbohydrate, and Bioactive. Sites 1 and 2 were grouped with nitrogen compounds, aromatic, lignin route, nitrogenated/oxygenated function, unspecific and cyclic aliphatic, while site 1 was closer to animal biomarkers. Sites 6 and 4 were grouped with lipid, hydrogenated function, fatty acid, bacteria G-, Ca, Cu, Mn, silt, and plant biomarkers.

In PCA associated with POM (Fig. 8b), just the sites 5 and 3 had proximity and shared associations with nitrogen compounds, vitamin, OM, Fe, clay, and amino acids properties. Site 1 was not grouped with other sites and is associated with hydrogenated function, unspecific biomarkers, nitrogenated/oxygenated function, Na, and bioactive. Site 2 was associated with microbial activity markers, animal biomarkers, and aliphatic. While site 4 is associated with G-, Mg, silt, aromatic, Ca, and pH H₂O, and has proximality with site 6, but differs when site 6 is associated more with lignin route, Cu, fatty acid, cyclic aliphatic, carbohydrate, Mn, G+, and plant biomarkers.

4. DISCUSSION

Our data on net ecosystem exchange of carbon dioxide in these Antarctica environments exhibit variations between sites and the interaction with plant covers and soil properties. These fluxes and their relationship are in accordance with Mendonça et al. (2010), who showed a clearly association between vegetation distribution and spatial variability of CO₂ emission.

Vegetated sites (sites 1, 5, and 6) showed greater temporal variability and CO₂ emissions than bare soils (sites 2, 3, and 4), resulting from plant respiration on CO₂-C emissions (Fig. 3a). These data corroborate the studies by La Scala et al. (2010), whose showed that soil thawing, longer daylight hours, and higher temperatures during the austral summer favor biological activity and release of easily decomposable root exudates by *D. antarctica*, showing 514 and 174% greater CO₂ emission in sites with *D. antarctica* and mosses, respectively. In our work, phanerogamic site 5 emitted 50 times and site 6, 129 times higher than the mixed site. The mosses present on site 1 are able to compensate for the source effect showing the highest sink effect and also for the lower positive values than sites with only vascular plants, resulting in a negative NEE ($-101.77 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). This sink mechanism and the moss occurrence restricted to this site may be associated with the local soil attributes. Site 5 and 6 present higher P values (114.8 and 128.6 mg/dm³, respectively) and higher OM (5.37 and 2.55 g kg⁻¹) than the mixed site (54.6 mg/dm³ and 1.75 g kg⁻¹). The mosses are coupled with poorly drained soils (Longton 1979) that result in greater organic carbon stocks. Therefore, mosses are responsible for greater soil organic carbon sink in terrestrial ecosystems of maritime Antarctica under anaerobic and hydromorphic conditions (Thomazini et al. 2019, 2016). The moss sink capacity in this site is combined with the organic matter characteristics (lower abundance of oxygenated functions - mainly in MAOM - and greater structural aromaticity of the molecules), which is also not grouped with any other site in the two PCAs (Fig. 8).

The net exchange of CO₂ showed a much greater difference between the grassy sites 5 and 6. This difference is attributed to biogeochemistry (soil and organic matter chemistry) and site biogeography (landscape position) and microbial community. These two areas have great potential for carbon source by high mineralization rates (max 4.96 and 4.38 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively), but site 6 showed a potential emission of CO₂ sum higher than site 5. The higher base sum (BS) on the top landscape position shows reduced loss of nutrients by leaching processes. But there is less OM compared with the lowest part of the landscape

which indicates that organic material is accumulating in lower sites in the landscape. Thomazini et al. (2016) showed a similar phanerogamic community release of $0.44 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in the austral summer of 2015, attributing it to higher mineralization associated with higher soil temperatures. When compared with 3.48 and $75.31 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in this study, sites 5 and 6 are releasing 7.9 and 171 times higher, respectively.

The absence of vegetation cover resulted in higher CO_2 emission potentials in sites 2, 3, and 4. A net loss of CO_2 was observed by Thomazini et al. (2016) in bare soil, associated with soil exposure that emitted $0.12 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ content, which is 3.66 times less than site 3. In site 3, the presence of higher organic matter (7.79 g kg^{-3}) represents a high availability of C (Barrett et al., 2006), and grouping with OM in the PCA (Fig. 8). In this landscape position, there is a large organic deposit that is losing the highest CO_2 value ($133.81 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). The increased microbiological activity of G+ bacteria (Fig. 7a), *Bacillus* (Fig. 7b), and nutrient availability (Table 4) make this site the largest CO_2 source in the landscape. It presents lower pH, Na^+ , BS, CECT, Ca^{2+} , and Mg^{2+} amounts, and the greatest values of H+Al, indicating a higher leaching degree (Daher et al. 2019) when compared with other sites. This leaching process can result in lower chemical protection of organic matter, removing salts that negatively affect the biochemistry of microorganisms (Tecon and Or 2017), which may facilitate mineralization (Łachacz et al. 2018) and CO_2 emission. Cannone et al. (2021) attributed higher CO_2 effluxes on barren soil to a higher content of soil organic matter that may provide support for more abundant soil bacterial components and provide more intensive respiration, with highest mean daily NEE of $0.19 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 17h in 2009, compared with a mean of $0.33 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in the same hour in this study (Fig. 4a), an increase of 73.6% in 10 years.

The soil organic matter quality is another determining factor for intensifying the CO_2 flux. This is defined as a set of properties that ease its mineralization (Plante 2010). Low-quality SOM has greater aromaticity, recalcitrance, lignin contents, and higher C/N ratio. While low amounts of lignin, C/N ratio, lower recalcitrance, and high amounts of sugars are attributed to greater OM quality (Syers 1997; Dignam et al. 2018; Signor et al. 2018; Mohamed et al. 2019), and easier degradation by the microbial community and greater CO_2 emissions (Laganière et al. 2012). Usually, SOM in Antarctic soils has high quality, and low C/N ratio (Beyer et al. 1999; 2000). The quality of light organic matter (POM) can be studied as a proxy for resistance to degradation, and CO_2 production. Better quality POM (greater abundance of carbohydrates and nitrogen compounds) was observed in sites 3, 5, and 6, which

also showed high CO₂ emissions. In PCA we can observe a positive correlation between CO₂ ($r = 0.55$ MAOM; $r = 0.57$ POM), aliphatic ($r = 0.49$ MAOM), carbohydrates ($r = 0.87$ POM) and oxygen functions ($r = 0.47$ MAOM, $r = 0.70$ POM). Zaccone et al. (2020) reported that the best quality POM (with proteins and carbohydrates) was quickly mineralized due to high enzymatic activities, in contrast with the longer mineralization of low-quality POM in Antarctica.

The organic matter associated with the mineral fraction (MAOM) is considered physically more protected, by clay association with from microbial activity (Hassink et al. 1997). However, the microbial community had greater access to MAOM at all sites, except in site 1, due to the greater abundance of bioactive, biopolymers, and microbial activity markers. One of the possible reasons for this to occur is the low physical protection offered by Antarctic soils, which have low clay contents (Łachacz et al., 2018). Thus, the production of bioactive substances (antimicrobial compounds/allelopathic) and biopolymers by vegetation (cuticles and waxes), the greater abundance of oxygenated functions, combined with microbial activity at sites 2, 3, 4, 5, and 6, and low mineral protection promote greater OM mineralization and soil respiration, resulting in higher CO₂ emissions.

The organic matter showed a predominance of oxygenated function in both POM and MAOM fractions, attributed to lipid abundance (type I kerogen). These organic molecules contributed to other high-quality compounds enhancing the potential CO₂ emissions by mineralization/oxidation (Harvey et al. 1986; Bjørlykke 2010). A study of CO₂, CH₄, and N₂O emissions from lake soils in a dry valley in Antarctica suggests that the amount and availability of O₂ plays an important role in mineralization processes on lakeshores (Gregorich et al. 2006). So, in the well-drained soils of Antarctica, a good supply of oxygen for the biochemical demand increases the O/C ratio, and greater CO₂ production by the oxidation of kerogen is possible (Toniolo and Carneiro 2015). Therefore, all sites, except site 1, have greater potential for CO₂ emission as they are richer in lipids, nitrogen, and organic matter, in both POM and MAOM. Showing that the greater aeration of the soil (due to drainage) and the oxygenated composition of the OM are potential drivers of Antarctic soil respiration, contributing to the positive feedback of CO₂ (Jian et al., 2018; Raich et al., 2002), in warming and melting scenarios.

The higher position in the landscape was a CO₂ emission variable with the greatest soil respiration. Dominated by vascular plants with higher rhizosphere activity (sites 5 and 6) or surrounded by them (sites 3 and 4), these sites are theoretically more drained due to the slope

of the relief and greater action of the rhizosphere, which promote greater soil respiration via the root, microbial community, and oxidation. In sites with *D. antarctica*, there is a large increase in microbial markers (Fig. 7a), positively associated with rhizosphere increase (Fierer et al. 2007; van der Heijden 2008; Barret et al. 2011) and soil drainage (Thomazini et al. 2016). In all of them, the greatest abundance of aerobic bacteria, *Bacillus*, *Arbuscular mycorrhiza*, *Sporosarcina sp.*, and proportion of G+/G- bacteria increase OM degradation and reflect CO₂ emissions. This CO₂ potential is attributed to a greater amount of OM, greater diversity of organic compounds in the POM, nitrogen in the MAOM, lignin derivatives, biopolymers, and phosphorus contents. In this context, studies have revealed higher biomass of G+ bacteria, *Arbuscular mycorrhizal* fungi, and Actinobacteria with increased C, N, recalcitrance, and reduced soil moisture, favoring grass systems (Mitchell et al. 2015; Yanardag et al. 2017; Brid et al. 2011; Fanin et al. 2019; Ghimire et al. 2019; Chen et al. 2020; Enggrob et al. 2020).

The PCA clustering resulted in an association between CO₂ emissions and phosphorus availability, G+ microbial biomass, oxygenated function, aliphatic compounds, and vascular vegetation (Fig. 8; Table A.4; A.5). Thus, the combination of phosphorus and aliphatic compounds favors mineralization by microbial communities, providing nutrients for plants. Phosphorus is one of the main limiting factors of microbial activity (Bragazza et al. 2019). When combined with quality organic matter, it drives CO₂ emissions. This is also observed in tropical regions, where CO₂ emission are limited by phosphorus availability (Hui et al. 2019).

A warming temperature scenario in these Antarctic ecosystems can result in increased C emissions, demonstrated by an exponential relation between CO₂ emissions and soil temperature, regardless of vegetation (La Scala et al. 2010; Carvalho et al. 2013). However, the CO₂ spatial variations appear to be more strongly related to the vegetation (La Scala et al. 2010; Mendonça et al. 2010) and the cumulative daily trends show that in many ways thermal increase and hydrological change can affect this dynamic releasing even more amounts of CO₂ (Table 6). The absence of vegetation cover resulted in the highest CO₂ emission, established in a C deposit with great potential to continue emitting and increasing following a temperature increase, with CO₂ amounts higher than values reported in previous years (Cannone et al. 2012; Thomazini et al. 2016). Vegetation communities composed of *D. antarctica* and newly exposed soils enhance their source effects following any warming trend, and the soil respiration by advancing grassy cover intensifies the CO₂ flows in a warming scenario, with a 230% emissions increase (Horrocks et al. 2020). The grassy sites have the

greatest CO₂ amplitude, indicating plastic response to short and medium-term varying environmental conditions (Brookes 1995; Chwedorzewska et al. 2004; Hill et al. 2019; Horrocks et al. 2020). In addition, moss NEE of CO₂ can be affected. Permafrost degradation and thawing of snow/ice promote hydromorphic areas (Turner 2005) and the establishment of moss carpets (Longton 1979). With increasing temperature, glacier retreat, and subsequent glacio-isostatic uplift, poorly drained areas tend to become well-drained, altering vegetation composition and declining their CO₂ sink effect (Thomazini et al. 2016).

5. CONCLUSIONS

1. In Demay Point, we found the highest mean CO₂ emission rate at a site with bare soil, due to organic matter deposited, soil microbial diversity, and the lack of vegetated cover;
2. The mixed community is the only CO₂ sink. This site has more aromatic compounds and lowers oxygenated functions in POM and MAOM. Despite having a greater abundance of microbial activity markers, it has less microbial abundance among the vegetated sites;
3. Interactions between vascular plants, soil microorganisms, and available phosphorus increase the degradation of higher quality OM and drive net CO₂ exchange;
4. The best quality organic material was composed of a greater abundance of carbohydrates, nitrogen and aliphatic compounds, and oxygenated functions.
5. Biomarkers of aquatic plants/moss indicate a large past contribution of non-vascular vegetation to the accumulation of OM from the studied Histosol. Biomarkers from vascular plants at sites with higher topography indicate a more recent contribution to the OM dynamics, under *D. antarctica*.
6. The increase in rhizosphere activity by vascular plants will increase soil respiration. We verified an increase in the abundance of phospholipid fatty acids (PLFA), mainly microbial, in vegetated sites, with greater expression in sites with *D. antarctica*. We also evidenced the increase of biomarkers of fungi and Gram-positive bacteria in the sites of higher topography, indicating more drained soils and intensification of the degradation of OM.
7. CO₂ dynamics of plant communities in Antarctica will respond to environmental changes differently depending on their plant and soil composition (microbial community and OM quality) and relief, however increasing NEE values.

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SUPPLEMENTARY MATERIAL

Table A.1: Organic compounds by the functional group with their respective molecules and average retention time of MAOM.

Organic compounds	Chemical name	Molecule	Chemical characterization	Ret. Time (minutes)
Amino Acid	DL-Proline, 5-oxo-, methyl ester	C ₆ H ₉ NO ₃	Aliphatic	7.33
	Decane, 3,7-dimethyl-	C ₁₂ H ₂₆	Aliphatic	6.52
	5,10-Diethoxy-2,3,7,8-tetrahydro-1H,6H-dipyrrolo[1,2-a:1',2'-d]pyrazine	C ₁₄ H ₂₂ N ₂ O ₂	Aromatic	16.81
Bioactive	9-Octadecenamide, (Z)-	C ₁₈ H ₃₅ NO	Aliphatic	33.06
	n-Tetracosanol-1	C ₂₄ H ₅₀ O	Aliphatic	29.60
	1-Heptacosanol	C ₂₇ H ₅₆ O	Aliphatic	40.64
	Nonacosane	C ₂₉ H ₆₀	Aliphatic	28.73
	Tetratetracontane	C ₄₄ H ₉₀	Aliphatic	41.17
	Heptadecane, 8-methyl-	C ₁₈ H ₃₈	Aliphatic	16.66
Biopolymer	Docosanoic acid, methyl ester	C ₂₃ H ₄₆ O ₂	Aliphatic	28.45
	Phenol, 2,6-dimethoxy-	C ₈ H ₁₀ O ₃	Aromatic	6.96
Carbohydrate	.alpha.-D-Glucopyranoside, methyl 2,3,4,6-tetra-O-methyl-	C ₁₁ H ₂₂ O ₆	Cyclic aliphatic	8.71
	.alpha.-D-	C ₁₁ H ₂₂ O ₆	Cyclic aliphatic	8.65

Lignin route	Mannopyranoside, methyl 2,3,4,6-tetra-O- methyl-			
	.beta.-D- Glucopyranoside, methyl 2,3,4,6-tetra-O- methyl-	C11H22O6	Cyclic aliphatic	8.47
	2,3,4- Trimethyllevoglucosan	C9H16O5	Cyclic aliphatic	7.40
	Benzoic acid, 3,4- dimethoxy- methyl ester	C10H12O4	Aromatic	10.07
	Benzenepropan oic acid, 4- methoxy-, methyl ester	C11H14O3	Aromatic	9.11
	Phenol, 2,4- bis(1,1- dimethylethyl)-	C14H22O	Aromatic	8.81
	Phenol, 3,4- dimethoxy-	C8H10O3	Aromatic	6.81
	1,2,4- Trimethoxyben zene	C9H12O3	Aromatic	7.10
	Octadecanoic acid, 10- methyl-, methyl ester, (R)-	C13H26O2	Aliphatic	22.54
	Pentadecanoic acid, methyl ester	C16H32O2	Aliphatic	13.39
Lipid	Hexadecanoic acid, methyl	C17H34O2	Aliphatic	16.20

ester			
Heptadecanoic acid, methyl ester	C18H36O2	Aliphatic	17.52
9-Octadecenoic acid, methyl ester, (E)-	C19H36O2	Aliphatic	19.87
Methyl stearate	C19H38O2	Aliphatic	20.42
Octadecanoic acid, 17-methyl-, methyl ester	C20H40O2	Aliphatic	22.52
Eicosanoic acid, methyl ester	C21H42O2	Aliphatic	23.79
1-Heneicosanol	C21H44O	Aliphatic	29.60
Heneicosanoic acid, methyl ester	C22H44O2	Aliphatic	26.53
1-Docosanol, methyl ether	C23H48O	Aliphatic	37.61
Docosanedioic acid, dimethyl ester	C24H46O4	Aliphatic	34.43
Tricosanoic acid, methyl ester	C24H48O2	Aliphatic	30.31
Tetracosanoic acid, methyl ester	C25H50O2	Aliphatic	32.12

	Hexacosane	C ₂₆ H ₅₄	Aliphatic	36.56
	Cholest-2-ene	C ₂₇ H ₄₆	Aliphatic	34.01
	Octacosanoic acid, methyl ester	C ₂₉ H ₅₈ O ₂	Aliphatic	38.75
	Triacontanoic acid, methyl ester	C ₃₁ H ₆₂ O ₂	Aliphatic	43.24
	Nonane, 5-(2-methylpropyl)-	C ₁₃ H ₂₈	Aliphatic	11.84
MMA	13-Docosenamide, (Z)-	C ₂₂ H ₄₃ NO	Aliphatic	33.06
	Hexacosanoic acid, methyl ester	C ₂₇ H ₅₄ O ₂	Aliphatic	35.54
	Pyrrolin-2-one-5-methanol, N-methyl-	C ₆ H ₁₁ NO ₂	Cyclic aliphatic	10.27
Nitrogen compounds	2,4(1H,3H)-Pyrimidinedione, 1,3-dimethyl-	C ₆ H ₈ N ₂ O ₂	Cyclic aliphatic	7.59
	2-Pyrrolidone-5-carboxylic acid, N-methyl, methyl ester	C ₇ H ₁₁ NO ₃	Cyclic aliphatic	6.86
	Caffeine	C ₈ H ₁₀ N ₄ O ₂	Aromatic	15.06
Others	Dodecane, 2-methyl-	C ₁₃ H ₂₈	Aliphatic	9.14
	Dodecane, 4-methyl-	C ₁₃ H ₂₈	Aliphatic	6.08

Heptadecyl trifluoroacetate	C ₁₉ H ₃₅ F ₃ O ₂	Aliphatic	23.80
Octacosane	C ₂₈ H ₅₈	Aliphatic	29.68
1-Propanol, 2- ethoxy-	C ₅ H ₁₂ O ₂	Aliphatic	5.99
Nonane, 1- iodo-	C ₉ H ₁₀ I	Aliphatic	6.08

Table A.2: Organic compounds by the functional group with their respective molecules and average retention time of POM.

Organic compounds	Chemical name	Molecule	Chemical characterization	Ret. Time (minutes)
Amino Acid	DL-Proline, 5-oxo-, methyl ester	C ₆ H ₉ NO ₃	Aliphatic	7.29
	2',4'- Dimethoxyacetophenone	C ₁₀ H ₁₂ O ₃	Aromatic	9.68
	1-Tridecene	C ₁₃ H ₂₆	Aliphatic	13.02
	5,10-Diethoxy-2,3,7,8- tetrahydro-1H,6H- dipyrrolo[1,2-a:1',2'- d]pyrazine	C ₁₄ H ₂₂ N ₂ O ₂	Aromatic	16.82
Bioactive	Oxacycloheptadec-8-en-2- one, (8Z)	C ₁₆ H ₂₈ O ₂	Cyclic aliphatic	20.94
	2-Nonadecanone	C ₁₉ H ₃₈ O	Aliphatic	46.42
	Heneicosane	C ₂₁ H ₄₄	Aliphatic	23.90
	2-methyloctacosane	C ₂₉ H ₆₀	Aliphatic	34.93
	Nonacosane	C ₂₉ H ₆₀	Aliphatic	23.71

	Tetratetracontane	C44H90	Aliphatic	41.18
Biop	Docosanoic acid, methyl ester	C23H46O2	Aliphatic	28.46
	.alpha.-D-Galactofuranoside, methyl 2,3,5,6-tetra-O-methyl-	C11H22O6	Cyclic aliphatic	6.02
Carbohydrate	.alpha.-D-Glucopyranoside, methyl 2,3,4,6-tetra-O-methyl-	C11H22O6	Cyclic aliphatic	8.74
	2,3,4-Trimethyllevoglucosan	C9H16O5	Cyclic aliphatic	7.39
	Benzoic acid, 3,4-dimethoxy-, methyl ester	C10H12O4	Aromatic	10.05
	2-Propenoic acid, 3-(3,4-dimethoxyphenyl)-, methyl ester	C12H14O4	Aromatic	15.58
Lignin route	Phenol, 2,4-bis(1,1-dimethylethyl)-	C14H22O	Aromatic	8.79
	Phenol, 3,4-dimethoxy-	C8H10O3	Aromatic	6.78
	1,2,4-Trimethoxybenzene	C9H12O3	Aromatic	7.07
	Nonanedioic acid, dimethyl ester	C11H20O4	Aliphatic	9.25
	Octadecanoic acid, 10-methyl-, methyl ester, (R)-	C13H26O2	Aliphatic	22.54
Lipid	Triacantanedioic acid, dimethyl ester	C15H28O4	Aliphatic	37.75
	n-Hexadecanoic acid	C16H32O2	Aliphatic	17.08
	Hexadecanoic acid, methyl ester	C17H34O2	Aliphatic	16.20

Octadecanoic acid	C18H36O2	Aliphatic	21.28
Methyl stearate	C19H38O2	Aliphatic	20.42
Nonadecanoic acid, methyl ester	C20H40O2	Aliphatic	22.52
Octadecanoic acid, 17-methyl-, methyl ester	C20H40O2	Aliphatic	22.53
Erucic acid	C22H42O2	Aliphatic	28.61
Hexanedioic acid, bis(2-ethylhexyl) ester	C22H42O4	Aliphatic	25.97
Heneicosanoic acid, methyl ester	C22H44O2	Aliphatic	26.53
13-Docosenoic acid, methyl ester, (Z)-	C23H44O2	Aliphatic	30.15
1-Docosanol, methyl ether	C23H48O	Aliphatic	36.67
Docosanedioic acid, dimethyl ester	C24H46O4	Aliphatic	34.44
Tricosanoic acid, methyl ester	C24H48O2	Aliphatic	30.31
Tetracosane	C24H50	Aliphatic	20.43
Tetracosanoic acid, methyl ester	C25H50O2	Aliphatic	32.12
Tricosanoic acid, 2-methoxy-, methyl ester	C25H50O3	Aliphatic	32.46
Stigmast-4-en-3-one	C29H48O	Cyclic aliphatic	43.67
Octacosanoic acid, methyl ester	C29H58O2	Aliphatic	38.76
Triacontanoic acid, methyl ester	C31H62O2	Aliphatic	41.78

MMA	Nonane, 5-(2-methylpropyl)-	C13H28	Aliphatic	8.55
	13-Docosenamide, (Z)-	C22H43NO	Aliphatic	33.09
	Morpholine, 4-octadecyl-	C22H45NO	Aliphatic	15.39
	Hexacosanoic acid, methyl ester	C27H54O2	Aliphatic	35.55
Nitrogen compounds	2,4(1H,3H)-Pyrimidinedione, 1,3,5-trimethyl-	C7H10N2O2	Cyclic aliphatic	8.23
	2-Pyrrolidone-5-carboxylic acid, N-methyl, methyl ester	C7H11NO3	Cyclic aliphatic	6.83
Others	Octane, 5-ethyl-2-methyl-	C11H24	Aliphatic	6.48
	Diethyl Phthalate	C12H14O4	Aromatic	10.15
	Dodecane, 4,6-dimethyl-	C14H30	Aliphatic	6.06
	1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	C16H22O4	Aromatic	15.13
	Hexadecane	C16H34	Aliphatic	9.83
	22-Tricosenoic acid	C23H44O2	Aliphatic	32.27
	Heptacosane, 1-chloro-	C27H55Cl	Aliphatic	38.15
	1,2-Cyclopentanedione, 3-methyl-	C6H8O2	Cyclic aliphatic	4.51
	Eicosane	C20H42	Aliphatic	13.71
	Hexadecane, 2,6,10,14-tetramethyl-	C20H42	Aliphatic	7.97
Vitamin	(+)-.alpha.-Tocopherol, O-methyl-	C29H50O2	Aromatic	37.38

Table A.3: Phospholipid fatty acids (PLFA) extracted from soil (name of compounds), molecular abbreviation of fatty acids and retention time.

Name of compounds	Molecular abbreviation of fatty acids	Retention time (minute)
Heptadecanal	17:0	8.81
Pentadecanal-	15:0	8.99
Pentadecanoic acid, methyl ester	15:0	11.29
Tridecanoic acid, 12-methyl-, methyl ester	15:0i	11.49
Hexadecanal	16:0	12.01
8-Hexadecenal, 14-methyl-, (Z)-	16:1ω7	13.48
Hexadecanoic acid, methyl ester	16:0	13.65
Hexadecanoic acid, methyl ester	16:0	14.52
Octadecanal	18:0	16.72
1-Heneicosanol	21:0	18.25
9,12-Octadecadienoic acid (Z,Z)-, methyl ester	18:2	18.50
9-Octadecenoic acid, methyl ester, (E)-	18:1	18.65
11-Octadecenoic acid, methyl ester	18:1ω7	18.79
Octadecanal	18:0	19.22
Heptadecanoic acid, 16-methyl-, methyl ester	17:0i	19.31
Octadecanamide	18:0	22.74
Pentadecanal-	15:0	24.91

Octadecanal	18:0	29.97
Octadecanamide	18:0	30.58
Tetracosanoic acid, methyl ester	24:0	31.36
22-Tricosenoic acid	22:0	31.50
Octadecanamide	18:0	31.89
Pentadecanoic acid, methyl ester	15:0	11.24
Tridecanoic acid, 12-methyl-, methyl ester	15:0i	11.43
9-Hexadecenoic acid, methyl ester, (Z)-	16:1ω7	14.00
9-Hexadecenoic acid, methyl ester, (Z)-	16:1ω7	14.22
Hexadecanoic acid, methyl ester	16:0	14.49
9,12-Octadecadienoic acid (Z,Z)-, methyl ester	18:2	18.49
9-Octadecenoic acid (Z)-, methyl ester	18:1	18.64
11-Octadecenoic acid, methyl ester	18:1ω7	18.78
Pentadecanal-	15:0	19.19
Heptadecanoic acid, 16-methyl-, methyl ester	17:0i	19.29
5,8,11,14-Eicosatetraenoic acid, methyl ester, (all-Z)-	21:0	22.93
Pentacosanoic acid, methyl ester	26:0	29.97
Octadecanamide	18:0	30.58
Tetracosanoic acid, methyl ester	24:0	31.36
Octadecanamide	18:0	31.89

Tetradecanoic acid, 12-methyl-, methyl ester	16:0a	11.27
Tetradecanoic acid, 12-methyl-, methyl ester	16:0a	11.47
Hexadecanoic acid, methyl ester	16:0	13.63
Methyl hexadec-9-enoate	16:1ω7	14.04
trans-13-Octadecenoic acid, methyl ester	18:1ω5	14.25
cis-10-Heptadecenoic acid, methyl ester	17:1ω7	15.41
9-Octadecenoic acid (Z)-, methyl ester	18:1	15.7
Hexadecanoic acid, 15-methyl-, methyl ester	16:0i	15.97
Hexadecanoic acid, 14-methyl-, methyl ester	16:0a	16.17
cis-10-Heptadecenoic acid, methyl ester	17:1ω7	16.28
Heptadecanoic acid, 10-methyl-, methyl ester	17:0a	17.80
9,12-Octadecadienoic acid (Z,Z)-, methyl ester	18:2	18.49
6-Octadecenoic acid, methyl ester, (Z)-	18:1ω12	18.67
9-Octadecenoic acid, methyl ester, (E)-	18:1	18.81
Methyl stearate	18:0	19.31
Docosanoic acid, methyl ester	22:0	29.96
Tricosanoic acid, methyl ester	23:0	30.74
22-Tricosenoic acid	22:0	31.50
Docosanedioic acid, dimethyl ester	24:0	31.99

Hexacosanoic acid, methyl ester	26:0	32.59
Hexadecane	16:0	7.02
Pentadecanoic acid, methyl ester	15:0	11.28
9-Hexadecenoic acid, methyl ester, (Z)-	16:1 ω 7	14.02
Hexadecanoic acid, methyl ester	16:0	14.50
9-Octadecenoic acid, methyl ester, (E)-	18:1	18.64
Methyl stearate	18:0	19.31
Heneicosanoic acid, methyl ester	21:0	31.37
22-Tricosenoic acid	23:0	31.50
Docosanedioic acid, dimethyl ester	24:0	32.19
Pentadecanoic acid, methyl ester	15:0	11.27
Tridecanoic acid, 12-methyl-, methyl ester	15:0i	11.47
Hexadecanoic acid, methyl ester	16:0	13.63
9-Hexadecenoic acid, methyl ester, (Z)-	16:1 ω 7	14.02
Pentadecanoic acid, 14-methyl-, methyl ester	15:0i	14.52
cis-10-Heptadecenoic acid, methyl ester	17:1 ω 7	15.40
Hexadecanoic acid, 15-methyl-, methyl ester	16:0i	15.97
Hexadecanoic acid, 14-methyl-, methyl ester	16:0a	16.17
9-Octadecenoic acid, methyl ester, (E)-	18:1	18.64
11-Octadecenoic acid, methyl ester	18:1 ω 7	18.79

Methyl stearate	18:0	19.31
Docosanoic acid, methyl ester	22:0	29.96
Tricosanoic acid, methyl ester	23:0	30.75
Tetracosanoic acid, methyl ester	24:0	31.37
22-Tricosenoic acid	22:0	31.508
Hexacosanoic acid, methyl ester	26:0	32.59
Pentadecanal-	15:0	8.89
Methyl tetradecanoate	14:0	9.76
Tetradecanoic acid, 12-methyl-, methyl ester	16:0a	11.25
Tetradecanoic acid, 12-methyl-, methyl ester	16:0a	11.44
Pentadecanoic acid, 14-methyl-, methyl ester	15:0i	13.61
9-Hexadecenoic acid, methyl ester, (Z)-	16:1ω7	14.01
trans-13-Octadecenoic acid, methyl ester	18:1ω5	14.23
Tetradecanoic acid, 5,9,13-trimethyl-, methyl ester	14:0i	15.52
Heneicosanoic acid, methyl ester	21:0	15.68
Hexadecanoic acid, 14-methyl-, methyl ester	16:0a	15.96
Hexadecanoic acid, 14-methyl-, methyl ester	16:0a	16.16
Heptadecanoic acid, 10-methyl-, methyl ester	17:0a	16.90

Heptadecanoic acid, 10-methyl-, methyl ester	17:0a	17.8
9-Octadecenoic acid, methyl ester, (E)-	18:1	18.64
11-Octadecenoic acid, methyl ester	18:1ω7	18.78
Methyl stearate	18:0	19.31
Octadecanamide	18:0	22.7
Heneicosanoic acid, methyl ester	21:0	29.97
Eicosanoic acid, methyl ester	20:0	31.38
Docosanedioic acid, dimethyl ester	24:0	31.98
Docosanedioic acid, dimethyl ester	24:0	32.18
Hexacosanoic acid, methyl ester	26:0	32.58

Table A.4: Significance levels based on Pearson's correlation coefficients between soil parameters and principal components from 6 different sites along the landscape related with Organic Matter Compounds Associated with the Mineral Fraction (MAON).

Soil parameters	Dim.1	Dim.2
pH H₂O	-0.93	-0.01
P (mg/dm³)	0.46	0.64
K⁺(mg/dm³)	0.60	-0.63
Na⁺(mg/dm³)	-0.47	-0.35
Ca²⁺(cmol/dm³)	-0.80	0.56
Mg(cmol/dm³)	-0.97	-0.03
Al³⁺(cmol/dm³)	0.70	-0.58
OM (g kg³)	0.94	0.06

Cu (mg/dm³)	-0.08	0.79
Mn (mg/dm³)	-0.41	0.53
Fe (mg/dm³)	0.83	-0.11
Zn (mg/dm³)	0.83	0.22
Sand (g)	0.59	-0.71
Silt (g)	-0.67	0.38
Clay (g)	0.37	0.34
CO₂ (μmol m⁻² s⁻¹)	0.55	0.68
Animal	0.02	-0.81
Gram - Negative (G- bacteria)	-0.46	0.60
Gram - Positive (G+ bacteria)	0.06	0.85
Plant	-0.09	0.57
Unspecific	-0.50	-0.67
Amino acids	0.39	-0.40
Bioactive	0.81	0.32
Biopolymer carbohydrate	0.59	0.42
Carbohydrate	-0.67	-0.33
Lignin route	-0.33	-0.77
Lipid	-0.57	0.68
Microbial activity markers	0.98	-0.15
N (Nitrogen compounds)	-0.27	-0.94

Aliphatic	0.49	0.70
Aromatic	-0.32	-0.77
Cyclic aliphatic	-0.59	-0.59
Nitrogenous oxygenated function	-0.29	-0.85
Hydrogenated function	-0.30	0.43
Oxygenated function	0.47	0.43
Hydrogenated function	-0.30	0.68
Fatty acid	-0.50	0.64

pH: active acidity, P: phosphorus, K⁺: potassium, Na⁺: sodium, Ca²⁺: calcium; Mg: magnesium; Al³⁺: exchangeable aluminum; OM: organic matter; Cu: copper; Mn: manganese; Fe: iron; Zn: zinc; CO₂: Average net CO₂ exchanges in the ecosystem. Dim1 and Dim2: axis of dimensions.

Table A.5: Significance levels based on Pearson's correlation coefficients between soil parameters and principal components from 6 different sites along the landscape related with Particulate Organic Matter (POM).

Soil parameters	Dim.1	Dim.2
pH H₂O	-0.17	-0.93
P (mg/dm³)	0.79	0.43
K⁺(mg/dm³)	-0.37	0.60
Na⁺(mg/dm³)	-0.29	-0.52
Ca²⁺(cmol_c/dm³)	0.52	-0.82
Mg(cmol_c/dm³)	0.03	-0.98
Al³⁺(cmol_c/dm³)	-0.48	0.69
OM (g kg⁻³)	0.001	0.95
Cu (mg/dm³)	0.93	-0.11
Mn (mg/dm³)	0.81	-0.42
Fe (mg/dm³)	0.13	0.82
Zn (mg/dm³)	0.43	0.84
Sand (g)	-0.62	0.62

Silt (g)	0.38	-0.72
Clay (g)	0.18	0.39
CO₂ (μmol m⁻² s⁻¹)	0.57	0.51
Animal	-0.91	0.01
G.- (G- Bacteria)	0.18	-0.48
G.+ (G+ Bacteria)	0.74	0.07
Plant	0.82	-0.06
Unspecific	-0.57	-0.55
Amino acids	-0.03	0.75
Bioactive	-0.70	-0.30
Biopolymer carbohydrate	0.79	0.36
Carbohydrate	0.87	-0.22
Lignin route	0.92	-0.12
Microbial activity markers	-0.68	-0.11
N (Nitrogen compounds)	-0.10	0.79
Vitamin	-0.10	0.90
Aliphatic	-0.72	0.27
Aromatic	0.34	-0.47
Cyclic aliphatic	0.88	-0.10
Hydrogenated function	-0.72	-0.48
Oxygenated function	0.70	0.43
Nitrogenous oxygenated function	-0.66	-0.39
Vascular plant	0.48	0.75
Fatty acid	0.82	-0.50

pH: active acidity, P: phosphorus, K⁺: potassium, Na⁺: sodium, Ca²⁺: calcium; Mg: magnesium; Al: exchangeable aluminum; OM: organic matter; Cu: copper; Mn: manganese; Fe: iron; Zn: zinc; CO₂: Average net CO₂ exchanges in the ecosystem. Dim.1 and Dim.2: axis of dimensions.

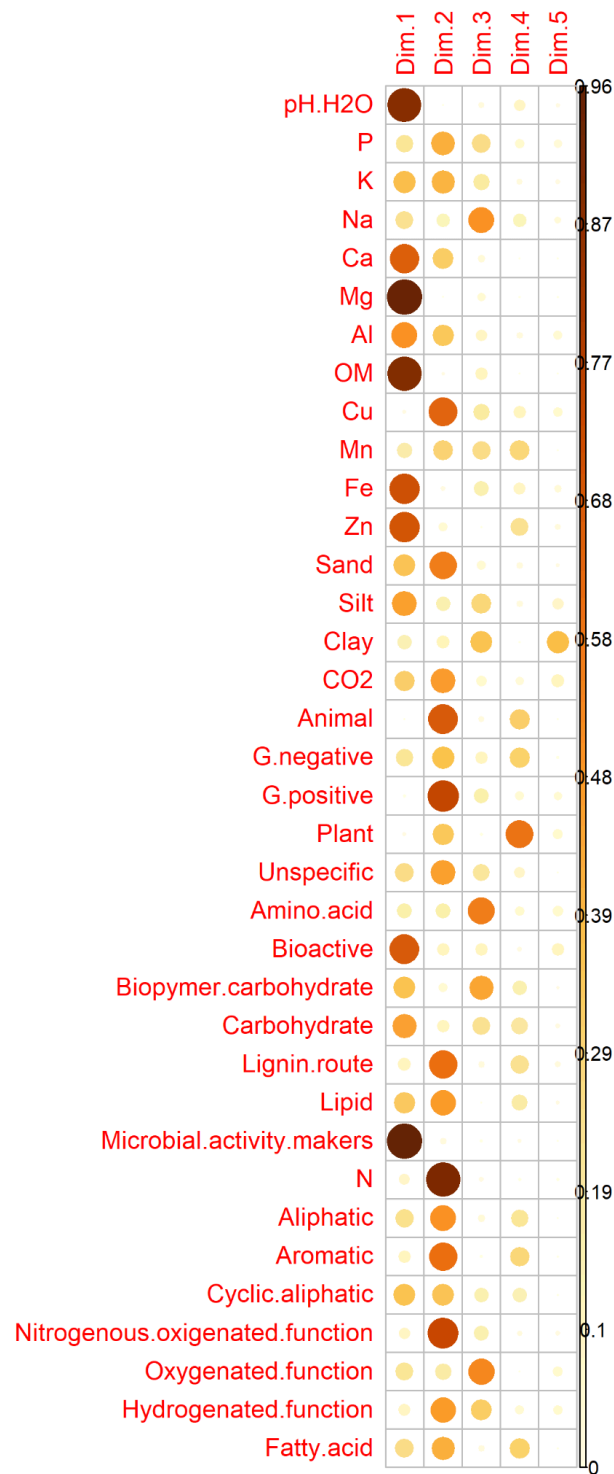


Figure 1.S: Correlation coefficients between soil parameters and principal components (Dim.1, Dim.2, Dim.3, Dim.4 and Dim.5) from 6 different sites along the landscape related with Organic Matter Compounds Associated with the Mineral Fraction (MAON).

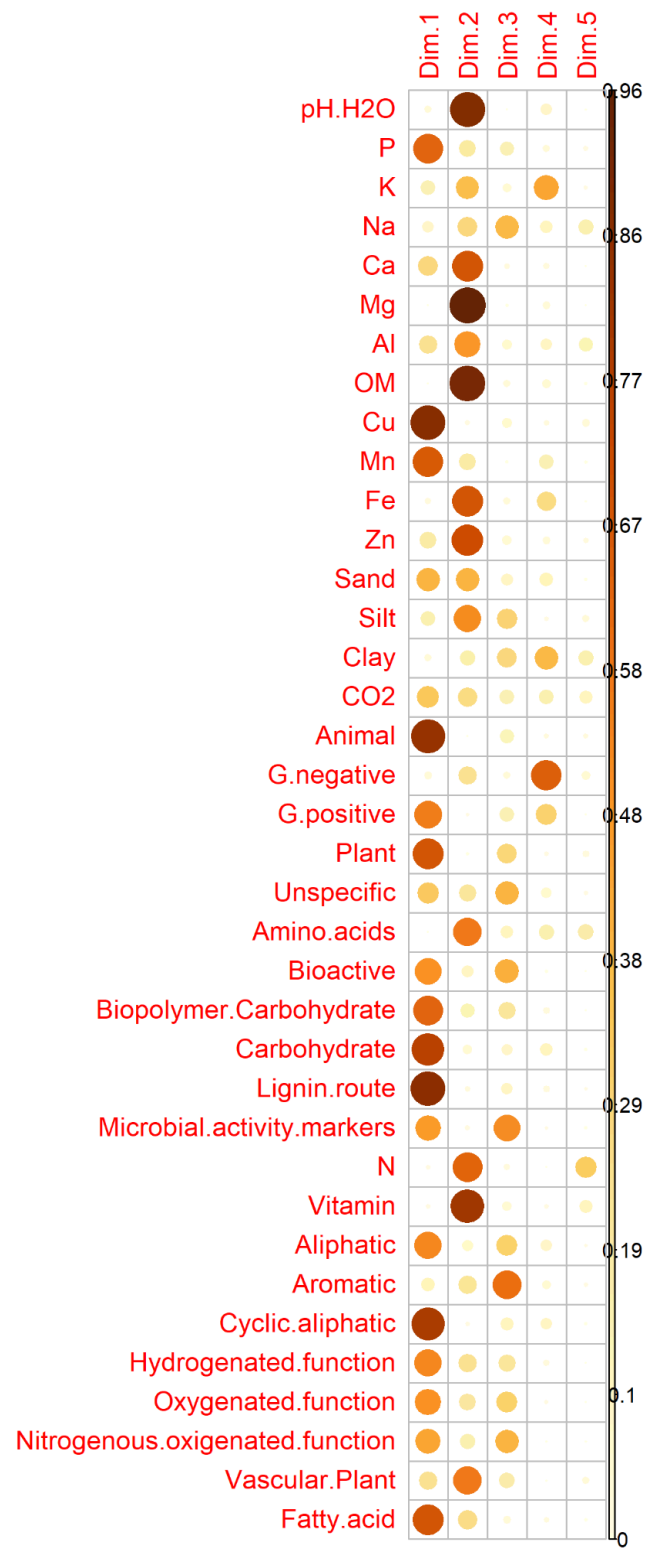


Figure 2.S: Correlation coefficients between soil parameters and principal components (Dim.1, Dim.2, Dim.3, Dim.4 and Dim.5) from 6 different sites along the landscape related with Particulate Organic Matter.

PARTE 2

CAPÍTULO III:

Habitat and soil-mediated filtering affect diversity in plant communities of Harmony

Point – Nelson Island

ABSTRACT

FERRARI, Flávia, D.Sc., Universidade Federal de Viçosa, May, 2022. **Habitat and soil-mediated filtering affect diversity in plant communities of Harmony Point – Nelson Island.** Adviser: Carlos Ernesto Gonçalves Reynaud Schaefer. Co-adviser: Marcio Rocha Francelino and Jair Putzke.

Species richness features prominently in foundational community ecology models and is a key taxonomical metric in conservation biology. In Antarctica, on a regional scale, the climate is the main driver that affects plant community diversity and structure. However, on a local scale, topography and soil properties are the more important factors. In this context, this study describes the patterns of habitat and soil that have a filtering effect on plant species distribution, richness, and community composition along environmental gradients on rocky outcrops with Giant-petrel nests. We hypothesize that plant species richness and plant composition are influenced by soil properties filters and by nests of Giant-petrels (proxy of habitat filtering) along rocky outcrops. We selected three rocky outcrops and analyzed plant frequency and coverage, richness patterns, and the main effects of potential predictors through models and soil analyzes. Therefore, we assumed that habitat-mediated filtering can determine species richness differences. This study reveals that changes in the substrate along the outcrops presumably also promote high species turnover between the three rocky fragments and emphasize the Antarctic vegetation responses to environmental changes with multiple scales.

Keywords: Antarctic vegetation. Plant-soil relationship. Cryptogamic communities. Species richness.

1. INTRODUCTION:

A key factor to determine plant diversity in Antarctica is soil properties and their processes of biogenic-abiogenic interactions (Abakumov et al., 2016; Convey and Smith, 2006; Smith, 1978). In Antarctica, these processes have been investigated in several studies (Bockheim, 2015; Almeida et al., 2014; Simas et al., 2007; Michel et al., 2006; Beyer et al., 1999). Soils chemical (nutrient availability), physical and biological factors drive the cryptogamic communities' mechanisms (Cannone et al., 2012; Simas et al., 2007; Robinson et al., 2003; Callaghan et al., 1992). Furthermore, microclimate factors, such as temperature (Kappen, 1985; Longton and Holdgate, 1967), moisture (Schroeter et al., 2017; Almeida et al., 2014; Schlensog et al., 2013; Kennedy, 1993; Schwarz et al., 1992), and landscape properties such as altitude and geomorphology can also influence plant diversity and composition (Ferrari et al., 2021; Schmitz et al., 2020a).

The climate-mediated filtering shaping species composition is referenced in various studies (Lee et al., 2017; Pincebourde et al., 2016). Abiotic factors (e.g., availability of water, energy, and nutrients), are considered the main driver of Antarctic species distribution (Chown et al., 2015; Convey et al., 2014; Hogg et al., 2006; Lee et al., 2004; Pereira and Putzke, 1994). Amorim et al. (2017) showed that local filters highly influence the distributions of bryophytes along geoenvironmental gradients. On a regional scale, climate is the main driver that affect plant community diversity and structure, however, on a local scale, topography and soil properties are the more important factors (Schmitz et al., 2020b; Medina et al., 2014). Schmitz et al. (2020a) demonstrate the effects of soil properties on species diversity and species composition along a pedoenvironment gradient in maritime Antarctica. Habitat filtering also can shape plant communities at smaller spatial scales, for example, the ice cover, ice scour, and salinity determine plant community diversity variability in Antarctica (Convey et al., 2014; Schmitz et al., 2020a, 2020b).

On the other hand, seabirds and marine mammals are vital for linking marine and terrestrial ecosystems (Qin et al., 2014), and are considered a key biological factor for plant communities (Olech, 2002). The birds nesting and organic matter deposition, as guano, particularly on elevated penguin rookeries and dispersed flying birds' nests (e.g., Giant-petrel – *Macronectes giganteus* Gmelin 1789, and skua – *Stercorarius* spp.), affects the diversity of plant communities and structure, predominantly along the coast (Abakumov et al., 2016). The areas manured create new conditions for the terrestrial biota development (Tatur 2002), making the local impact of birds presence particularly important since they contributed to

nutrient inputs for the poor Antarctica ecosystems (Bokhorst et al., 2007; Myrcha and Tatur, 1991).

The study of vegetation distribution in these areas aims to understand the colonization process in newly exposed areas and how climate change can interfere in their development (Robinson et al., 2018). These plant-seabirds interaction studies have already been conducted (Albuquerque et al., 2012). On Elephant Island, there is a positive relationship between vegetation cover and giant petrel nests area, which may indicate that active nests promote higher species richness, community composition variability, and beta diversity (Putzke et al., 2022). On King George Island, the penguin-derived fertility determines the vegetation zonation pattern (Smykla et al., 2007). The lowest species number occurred within the penguin rookeries. When decreasing their impact, there was an increase in plant species richness and diversity, with a simultaneous decrease in species dominance (Smykla et al., 2007). In East Antarctica, moss and lichen species diversity and mean lichen species abundance were higher in sites adjacent if compared to those away from seabirds nests, where the input of ornithogenic products resulted in increased lichen species abundance and diversity (Leishman and Wild, 2001). A penguin-derived fertilizer input allows the concentration of nutrients to fall to levels favorable for the growth of many different taxa, enabling more diverse plant assemblages to develop (Smykla et al., 2007). On the other hand, the toxic levels of manuring and the effects of trampling by dense penguin populations cause vegetation damage (Rakusa-Suszczewski et al., 1998; Tatur et al., 1997; Zwolicki et al., 2015). Although, the relict orthogenic soils in abandoned rookeries are also important sources of nutrients (Myrcha and Tatur, 1991; Tatur and Myrcha, 1989).

Soil development is also affected by flying birds' transportation activity, while they transport the viable diaspores of plants and material of limpet shells, etc (Abakumov et al., 2016). In addition, birds can use plants to make their nests, like skuas on Polytriciaceae patches (Quintana et al., 2001), and can be mixtures with lichens or flowering plants like kelp gulls - *Larus dominicanus* Lichtenstein (1823) – which used mainly *D. antarctica* (Quintana et al., 2001). The vegetation around the isolated nests of flying birds is usually not devastated, because there is moderate input of nutrients around these nests which acts as a fertilizer and stimulating the growth of various taxa (Smykla et al., 2007).

Despite the importance of ornithogenic soils highlighted in Antarctic research, studies on the influence on the soil by flying birds and how these soil properties can be an important environmental filter of species are poorly known (Lopes et al., 2022). Among the different

scales used to quantify the biodiversity of species, species richness is the most frequently treated (Feurerer and Hawksworth, 2007).

In this context, this study purposed to describe the patterns of habitat and soil that have a filtering effect on plant species distribution, richness, and community composition along environmental gradients on rocky outcrops with Giant-petrel nests in Nelson Island, maritime Antarctica. Nesting is an interference factor in plant communities in coastal areas of maritime Antarctica. Thus, we hypothesize that plant species richness and plant composition are influenced by soil properties filters and by nests of Giant-petrels (proxy of habitat filtering) along rocky outcrops.

2. MATERIAL AND METHODS

2.1 SITE DESCRIPTION

Nelson Island, with an area of about 200 km², is located southwest of King George Island, as part of the South Shetland Islands, separated by a small sea inlet (400 m), the Fildes Strait. The ice-free areas of Nelson Island, Harmony Point (Figure 1b) are in the western sector of the island.

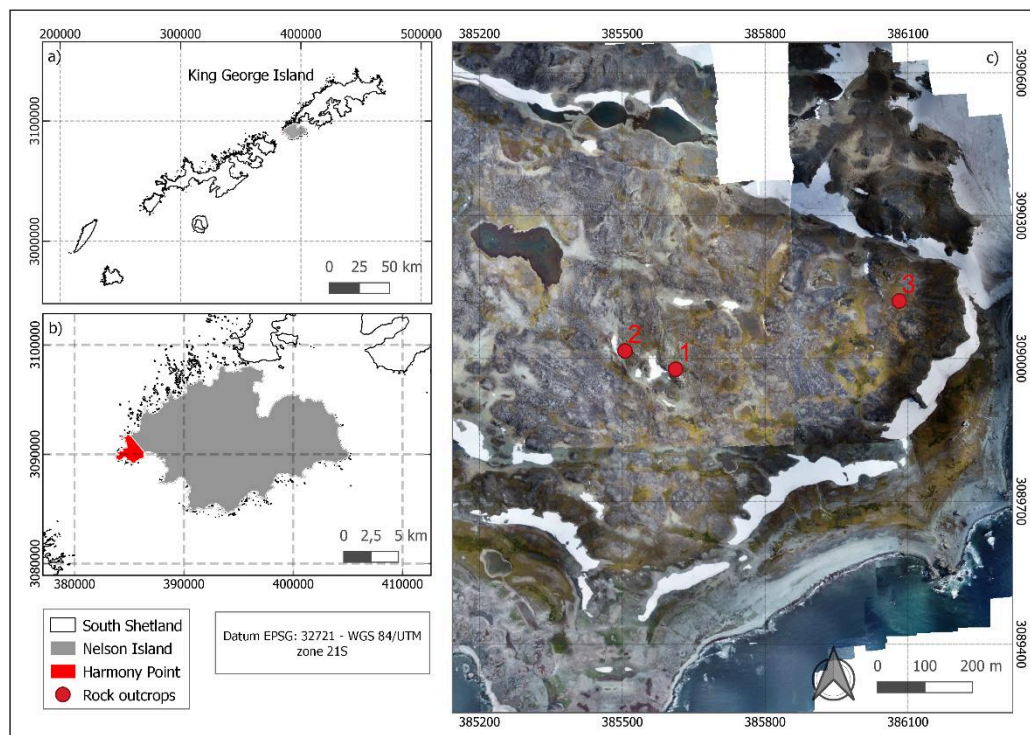


Figure 1. Localization of the study area and the respective sampling rocky outcrops points. a) The South Shetland Archipelago highlighting Nelson Island next to King George Island; b) Location of Harmony Point on Nelson Island; c) An aerial image showing the three rocky outcrops sampling on Harmony Point (red dots).

The region is part of the Antarctic Specially Protected Area (ASPA) n° 133, representing a priority area for biodiversity preservation due to its diverse bird community and extensive and varied vegetation cover. The area hosts a large diversity of breeding seabirds, including one of the largest colonies of chinstrap penguins (*Pygoscelis antarctica*) in Antarctica. There is also a large giant petrel colony, which is highly sensitive to human disturbance (Management Plan for Antarctic Specially Protected Area No. 133, 2005). The average monthly air temperature varies between -6.4 °C in July and + 2.3 °C in February. The average annual precipitation is 367 mm (INPE 2009).

According to Rodrigues et al. (2019), Harmony Point is divided into two major landscape units, the coastal domain, and the upper platform. Both can be occupied by marine birds, resulting in widespread ornithogenic activity and well-developed soils and vegetation.

2.2 SAMPLING SITES

We selected three rocky outcrops with giant petrel's nesting influence. Rocky outcrops A1 (Fig. 2a) and A2 (Fig. 2b) present active nests. Rocky outcrop A3 was not active in the summer period during this research. However, there were traces of abandoned nests (Fig. 2c). The Harmony Point region was mapped with a drone (Phantom 4Pro model) creating an orthomosaic with 0.05 m resolution using Agisoft Photoscan software (Fig. 1c). In the Q-GIS software, we measured the total rocky outcrops' length.

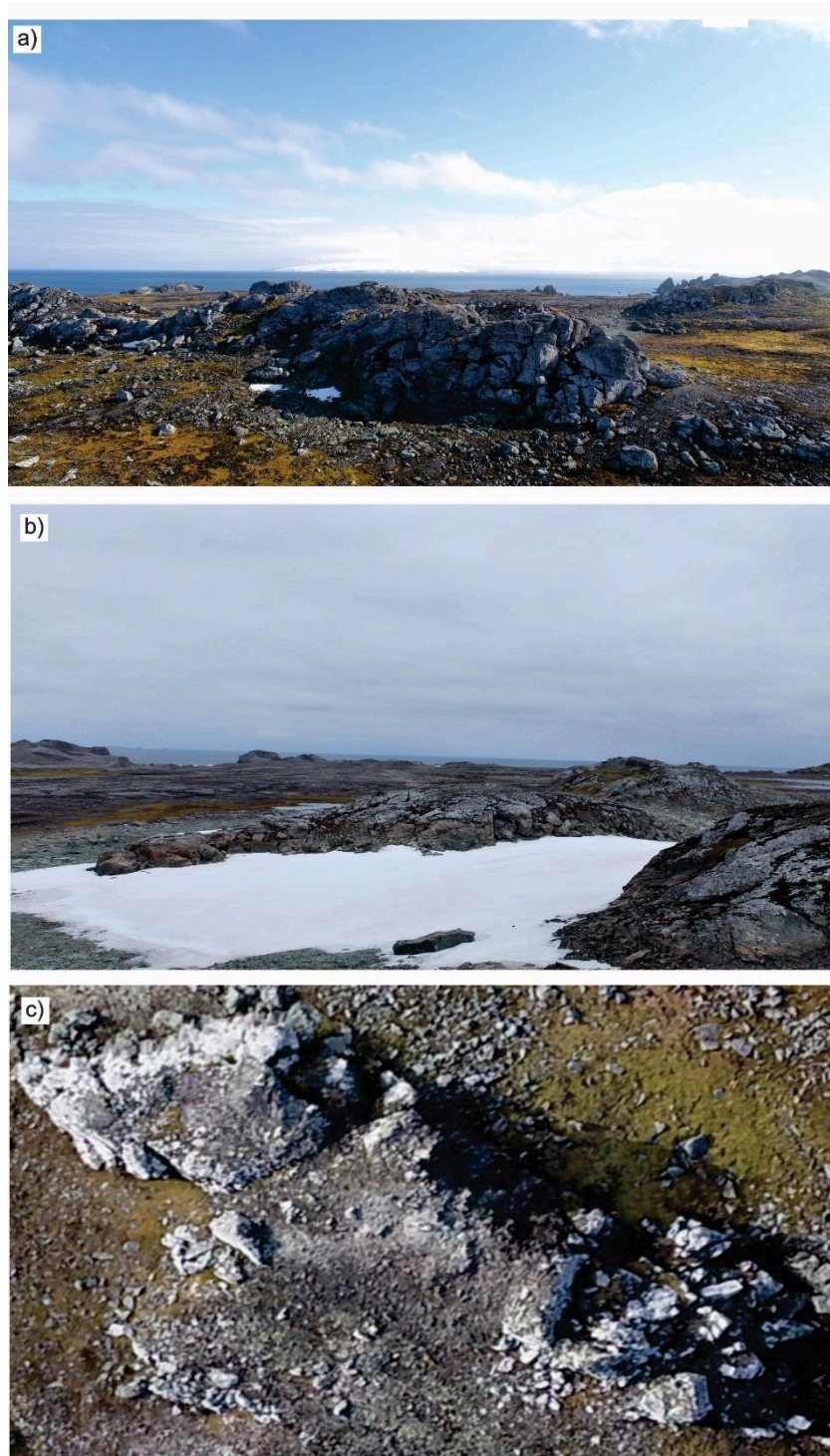


Figure 2. General characteristics in the landscape of the a) rocky outcrop A1, b) A2, and c) A3, studied in Harmony Point, Nelson Island.

2.3 VEGETATION MAPPING

To analyze the non-vascular plant cover, we used the method adapted to Antarctic conditions (Schmitz et al., 2018), tracing lines with 5-meter spacing. The total number of lines and the distance depended on the total length of each outcrop. In each line, we describe seven plots that crossed the outcrops in the north-south direction and returned south-north including

the rocky outcrops' surroundings. The plots were 20 cm x 20 cm, subdivided into 100 smaller squares.

We estimated the plant coverage (%) of each species represented by the presence in the smaller squares, thus representing the specie occupying proportion. Besides that, we estimated the relative frequency (F) of the species, calculated by the number of occurrences (x) divided by the total number of samples considered (n):

$$F = 100x/n \quad (1)$$

The substrates were distinguished in two environments, called groups. The plots representing a rock fragment (substrate) were denominated A, and plots representing bare soil in the rock surrounding fragments were denominated B to compare species richness in two distinguished substrates.

To identify plant species we used specific literature, such as Putzke and Pereira (2001) and Ochyra et al. (2008) for mosses, and Ovstedal and Smith (2001) and Olech (2004) for lichens, when possible.

2.4 SOIL PHYSICAL AND CHEMICAL COLLECTION AND ANALYSES

In each plot analyzed we collected a single soil sample (0-10 cm depth) for soil properties quantification. The samples were stored, identified in plastic bags, and transported to the TERRANTAR laboratory at the Universidade de Viçosa. Samples were dried at air temperature, and sieved (2mm mesh) to separate the stony fraction.

We measured the following chemical properties pH (H₂O), P, K⁺, Na⁺, Ca²⁺, Mg²⁺, Al³⁺, total acidity (H +Al), bases sum (BS = Ca²⁺+Mg²⁺+Na⁺+K⁺), effective cation exchange capacity (CECeff), total cation exchange capacity (CECT), bases saturation (V%={100BS}/CECT), aluminum saturation (m={Alx100}/CECeff), sodium saturation index (ISNa%={100xNa}/CECeff), organic matter (OM), remaining phosphorus (P-Rem), Cu, Mn, Zn, and total nitrogen (N). The physical properties analyzed were soil texture, classified as sand, silt, and clay contents. All analyzes followed standard protocols (Teixeira et al., 2017).

2.5 STATISTICAL ANALYSES

General soil properties were summarized using descriptive statistical analyses (mean, median, maximum, minimum, 1st and 3rd quartile, and coefficient of variation). All data and statistical analyses were conducted in R Environment 4.1.2 (R Core Team, 2019). To illustrate, we used the package “ggplot2” (Hadley, 2015).

Soil attributes were subjected to principal component analysis (PCA) reducing redundant soil properties, to identify highly weighted soil variables that best represented the relationships between soil composition and rocky outcrops. The PCA analysis was carried out using “FactorMiner” (Husson et al., 2017) and “factoextra” (Kassambara and Mundt 2020) packages, and illustrated by “ggplot2” (Hadley, 2015).

To compare and demonstrate the plant species richness between the rocky outcrops, we prepared Venn diagrams according to Dusa (2021), using set intersections in the “Venn” and “vennDiagram” package (Chen, 2021).

We analyzed the species richness patterns between rocky outcrops and between environments estimating rarefaction and extrapolation curves based on the 100 replicate bootstrap runs to estimate 95% confidence intervals of interpolated and extrapolated curves (A. C. Rodrigues et al., 2019; Schmitz et al., 2020a). Extrapolations were based on the presence/absence of species in each plot using Hill number order 0 to evaluate the plot sufficiency in each rocky outcrop (Colwell et al., 2012), and the package “iNEXT” provided the estimates (Hsieh et al., 2016).

We tested the normal distribution using the Shapiro-Wilk test for all variables and evaluated the Q-Q plot and the homogeneity of variances by Bartlett’s test. We performed non-metric multidimensional scaling (NMDS) to analyze differences between rocky outcrops and between environments in terms of plant species richness using Euclidean dissimilarities (Clarke, 1993). We performed NMDS through the “vegan” package, using the ‘metaMDS’ function (Oksanen et al., 2018). We used Permutational multivariate analysis of variance (PERMANOVA) to determine differences in species composition (9999 permutations) through the ‘adonis routine’ from the “vegan” package (Oksanen et al., 2018).

To explain the main effects of potential predictors on species richness and community composition (using NMDS as a proxy of species composition variability) we analyzed the linear mixed effect models (LMMs) (Schmitz et al., 2020a; Villa et al., 2018). We used the axes of the PCA for soil fertility (PCA1f) and texture (PCA1t) variables to reduce any strong correlations among local environmental conditions (Table S2). Thus, the first PCA axis was considered as a proxy for soil texture gradient across all the tested models (Villa et al., 2018). We used generalized linear effects models (GLMMs) with Poisson error distribution to investigate the effect of soil fertility and soil texture on species richness and composition. Species richness and composition were assessed using LMMs after checking the Shapiro-Wilk test for normality and Q-Q graph (Crawley, 2013). Predictor variables (fixed effects)

were plant coverage, soil fertility (PCA1f), and soil texture (PCA1t), defined as the first principal component from PCA with 15 soil properties analyzed (Schmitz et al., 2020b, 2020a; Villa et al., 2018). In all models, we included the environmental groups as a random factor. We processed the models through the ‘lme4’ package (Bates et al., 2014).

3. RESULTS

3.1 SOIL PROPERTIES

In 121 phytosociology plots, we could analyze 97 soil samples due to the adversities like rocky substrate, ice cover, and insufficient content for sampling.

In average general, soils from rocky outcrops were strongly acidic (4.87 pH to 5.0 average), have low fertility, and were considered dystrophic (BS = 4.23 to 6.89 cmol_c/dm³ and V = 18.93 to 23.7%). Comparing the three fragments, A3 presents the highest individual values of P (104.0 to 1126.7 mg/dm³), clearly influenced by guano deposition, while A2 presents the highest OM, reaching 59.56 dag/kg and Na hit 442.57 mg/dm³. A1 presents the highest total N content plot with 1121.2 mg/dm³ (Table 1).

When observing the means values, A2 presents higher K (141.48 mg/dm³), Na²⁺ (256.86 mg/dm³) and N values (0.97 mg/dm³). A3 had higher fertility (Ca²⁺ = 2.28 mg/dm³, Mg²⁺ = 1.28 mg/dm³) and higher P (290.42 dag/kg) (Figure 3). The amounts of OM varied between 16.33 dag/kg in A1, 19.8 in A2, and the highest mean of 23.11 dag/kg in A3. Soils had a sandy clay loam texture (Table 2), dominated by the sand fraction (coarse/fine sand) (Figure 4).

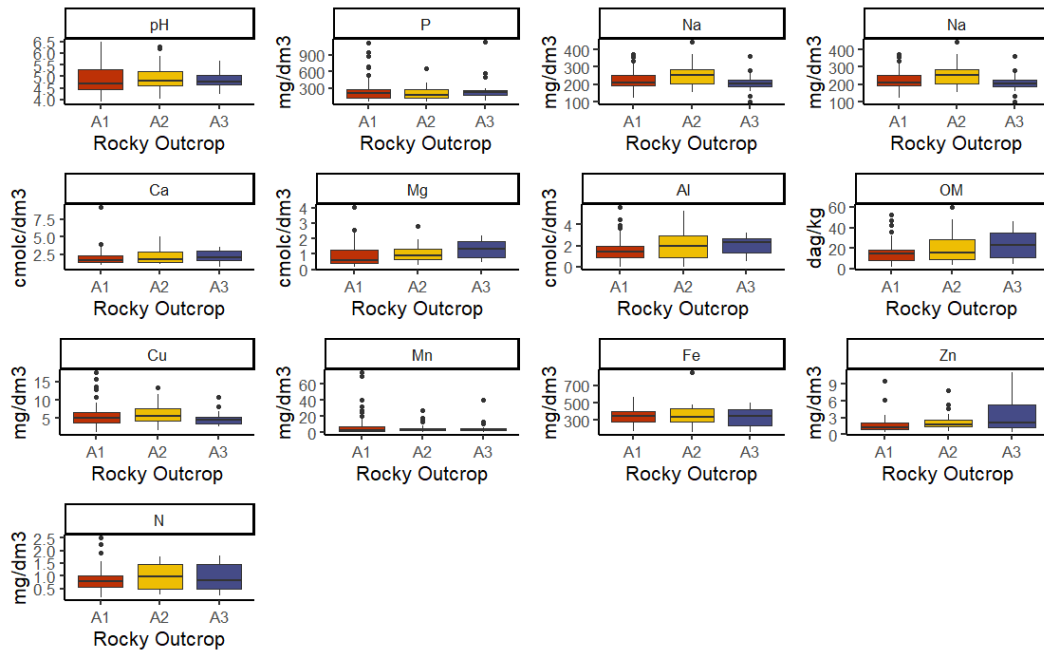


Figure 3. Descriptive statistics of soil properties analysis of the three rocky outcrops in Harmony Point, Nelson Island. pH: active acidity (H_2O); P: phosphorus; K: potassium; Na: sodium; Ca: calcium; Mg: magnesium; Al^{3+} : exchangeable aluminum; OM: organic matter; Cu: copper; Mn: manganese; Fe: iron; Zn: zinc; N: total nitrogen.

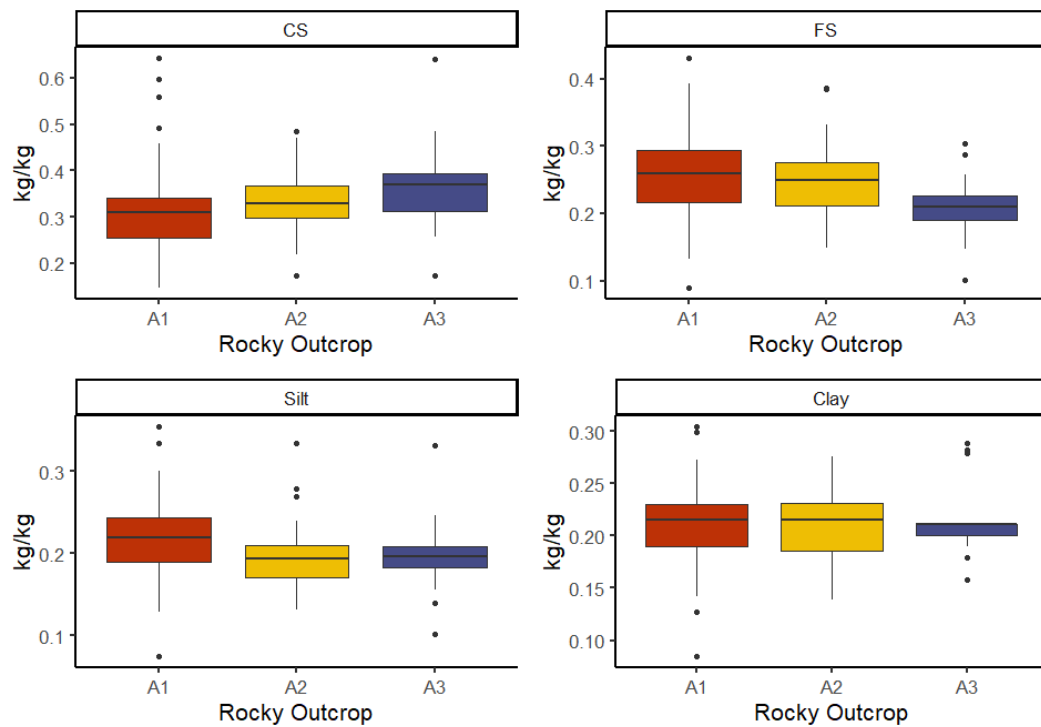


Figure 4. Soil physical characterization along three rocky outcrops was analyzed in Harmony Point, Nelson Island. CS: Coarse sand; FS: Fine sand.

The first two axes of the soil properties in the principal component analysis (PCA) explained 55.4% of the data variance (Figure 5). Although the PCA did not clearly separate

into groups, it grouped the rocky outcrops with the chemical and physical properties in common. The first axis (Dim1) explained 30% of the variance and was positively correlated with Mn ($r = 0.83$; $p < 0.05$), Ca ($r = 0.76$; $p < 0.05$), and pH ($r = 0.74$; $p < 0.05$). Conversely, the axis was negatively correlated with OM ($r = -0.23$; $p < 0.05$), N ($r = -0.32$, $p < 0.05$), and Clay ($r = -0.43$; $p < 0.05$). The second axis (Dim2) explained 25.4% of the variation and was correlated positively with MO ($r = 0.84$; $p < 0.05$), N ($r = 0.79$; $p < 0.05$), and Al ($r = 0.69$; $p < 0.05$) (Table S1), and negatively correlated with pH ($r = -0.44$; $p < 0.05$), and Fe ($r = -0.44$; $p < 0.05$).

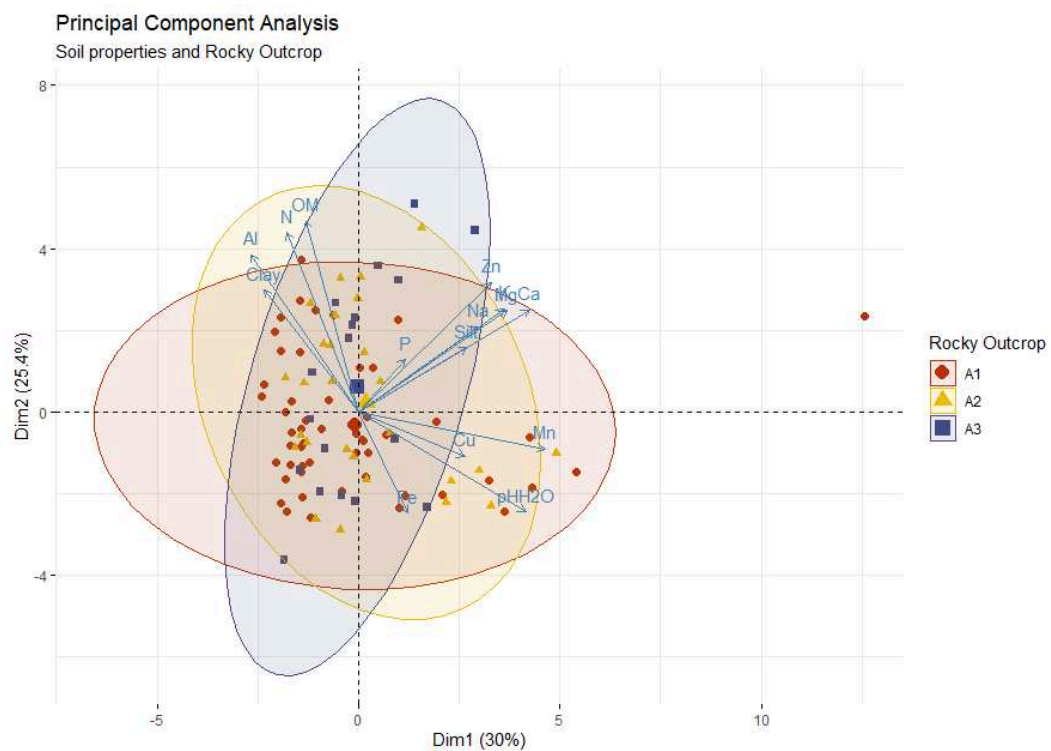


Figure 5. Biplot of the Principal Component Analysis (PCA) for the soil parameters of three rocky outcrops in Harmony Point, Nelson Island. Dim = axis.

Table 1. Chemical properties of the soil samples from different rocky outcrops in Harmony Point – Nelson Island.

Rocky Outcrop	Env *	Plot	pH H ₂ O	pH KCl	P	K	Na	Ca	Mg	Al	H+Al	BS	CE Ct	CEC T	V	m	ISN _a	OM	P-Rem	Cu	Mn	Fe	Zn	N
					mg/dm ³					cmol/dm ³					%			dag/kg	mg/L	mg/dm ³				
A1	B	P1	5.4 9	4.2 7	61.7 4	12 48	255. 3	3.2 3	2.4 3	1.0 5	14.6	7.09	8.14	21.6 9	32.7 9	12. 9	5.12	17.27	3	4.48	20. 8	548. 2	1.42	0.8 8
A1	B	P2	5.8 5	4.3 8	221. 8	10 9	204. 57	2.2 1	1.3 7	1.0 5	17.3	4.75	5.8	22.0 5	21.5 1	18. 1	4.03	10.56	4.5	10.8 6	27. 7	490. 8	0.44	0.5 8
A1	B	P3	5.4 5	4.3 5	101. 2	66 72	337. 8	1.4 8	0.7 9	1.0 5	16.5	3.91	4.96	20.4 1	19.2 2	21. 2	7.19	10.24	2.2	4.43	7.1	385. 6	0.75	0.5 8
A1	B	P4	4.7 5	4.1 6	79.1 6	95 74	196. 4	2.0 5	1.2 5	2.1	20.6	4.39	6.49	24.9 9	17.6 4	32. 4	3.42	19.19	0.9	3.29	6.6	384	1.15	0.8 8
A1	B	P5	4.8 8	4.1 6	179. 6	11 7	200. 65	2	1.3	1.9	19	4.47	6.37	23.4 7	19 8	29. 8	3.72	17.59	4.5	4.15	13. 3	441. 6	1.95	0.6 4
A1	B	P6	4.5 2	4.0 7	258. 6	76 3	357. 2	1.5 2	0.5 4	3.2 4	27.8	3.81	7.05	31.6 1	12.1	46	4.91	25.59	0	3.38	2	173. 9	1.54	1.1 0
A1	B	P7	5.8 8	4.6 9	66.6 3	16 47	302. 8	3.9 8	2.5 7	0.1 9	7.2	8.28	8.47	15.4 8	53.5	2.2	8.5	7.04	8.9	4.04	69. 4	565. 4	3.16	0.3 4
A1	B	P8	5.2 2	4.4 1	212. 8	10 9	208. 48	1.9 2	0.8 3	0.6 7	14.5	3.94	4.61	18.4 4	21.4 5	14. 5	4.92	22.39	3.9	6.57	3.5	270	2.38	0.8 6
A1	B	P9	4.3 4	4.0 5	169. 9	85 21	361. 5	1.5 2	0.4 2	3.7 1	31.1	3.76	7.47	34.8 6	10.8 7	49. 7	4.51	4.16	0	3.38	1.4	169. 2	1.58	1.2 6
A1	B	P10	4.9 6	4.2 5	486. 3	11 9	220. 23	2.9 9	1.0 4	1.2 4	18.8	5.25	6.49	23.3 1	22.0 5	19. 1	5.17	42.22	3.7	1.28	2.9	224. 4	2.42	2.2 3
A1	B	P12	4.2 7	4.1 5	175. 5	10 7	216. 32	1.4 5	0.5 2	1.8 1	15.1	3.18	4.99	18.2 8	17.4 3	36. 3	5.15	15.99	4	4.23	1.8	311	1.02	0.6 3
A1	B	P14	4.8 5	4.1 6	84 6	13 06	275. 9	3.4 9	2.4 7	1.8 1	21.8	7.5	9.31	29.3	25.6	19. 4	4.08	32.62	1.1	2.72	5.8	226. 4	2.27	0.6 3
A1	B	P15	4.6 2	4.2 2	82.7 1	12 31	263. 31	2.6 1	1.7 1	1.5 2	15.9	5.77	7.29	21.6 7	26.6 9	20. 9	5.28	17.91	1.7	4.87	16. 7	320. 6	1.47	1.4 6
A1	B	P16	5.7 6	4.4 4	188 4	13 98	231. 7	3.1 8	1.8 8	0.3 8	10.8	6.4	6.78	17.2	37.2	5.6	5.86	8	6	6.34	40. 2	531. 2	1.18	0.7 0
A1	B	P18	4.3 5	3.4 2	1121 9	18 47	302. 7	1.6 6	0.4 2	3.5 2	39.4	3.93	7.45	43.3 3	9.1 2	47. 2	3.04	22.39	16.7	5.23	1.7	410. 9	1.74	0.4 4
A1	A	P20	4.0 8	3.3 2	879. 8	85 47	302. 7	1.6 6	0.4 2	3.5 2	34.4	2.42	6.32	36.8 2	6.6 7	61. 7	1.51	17.91	21.6	5.24	1.3	423. 2	1.14	1.5 2
A1	B	P21	4.6 7	3.8 1	142. 5	11 3	302. 47	1.6 7	0.4 6	3.5 2	37.1	4.7	9.18	41.8	11.2	48. 8	2.54	52.46	0.6	2.75	2	304. 2	2.66	1.5 7
A1	A	P22	4.7 2	4.1 5	334. 1	10 1	302. 47	1.6 7	0.4 6	3.5 2	14.9	2.67	3.91	17.5 7	15.2 7	31. 7	4.77	12.79	4.6	5.03	1.4	258. 3	1.38	0.8 3
A1	A	P23	6.4	4.9	694.	31	302.	1.6	0.4	3.5	3.8	15.6	15.6	19.4	80.4	0	8.35	1.92	29	15.7	74.	351.	9.49	0.1

			7	1	5	5	47	7	6	2		1	1	1					9	2	6		7	
A1	B		6.0	4.7	534.	17	302.	1.6	0.4	3.5	5.3	6.86	6.86	12.1	56.4	0	10.9	5.76	21.9	7.48	12.	305.	6.12	0.3
		P24	5	7	7	3	47	7	6	2				6			6			5	4		5	
A1	B		5.2	4.4	262.	12	302.	1.6	0.4	3.5	10.5	2.99	3.66	13.4	22.2	18.	6.72	4.16	6	9.32	14.	453.	1.33	0.3
		P25	4		5	2	47	7	6	2				9		3				5	9		2	
A1	A		4.2	3.9	127.	78	200.	1.6	0.6	2.9	22.5	3.36	6.31	25.8	13	46.	3.37	24.95	2.2	1.75	1.6	369.	1.07	0.9
		P28	5	5	7		65	4	5	5				6		8					2		9	
A1	B		4.5	3.9	87.7	11	208.	2.6	1.5	3.5	29.2	5.4	8.92	34.6	15.6	39.	2.62	52.46	0	2.85	3.4	298	2.33	1.4
		P31	7	5		9	48	9		2						5							6	
A1	B		4.5	4.1	272.	99	192.	1.5	0.3	1.9	16.2	3.02	4.92	19.2	15.7	38.	4.36	16.63	3.1	6.13	2.1	334.	1.14	0.7
		P32	2		3		82	7	6					2		6					8		0	
A1	B		4.2	4.1	194.	97	186.	1.2	0.3	1.1	11.9	2.65	3.79	14.5	18.2	30.	5.57	8.96	7.9	5.08	2.2	406.	0.86	0.3
		P33	9	9	6		48	2	7	4				5		1					4		8	
A1	B		4.2	3.9	254.	10	204.	1.2	0.4	2.7	23.1	2.89	5.65	25.9	11.1	48.	3.42	19.83	3.4	6.16	2.1	400.	1.14	1.1
		P34	5	8	8	7	57	5	8	6				9		8					1		4	
A1	A		4.2	4.1	257.	12	196.	2.1	0.8	5.6	40.1	4.14	9.76	44.2	9.4	57.	1.93	47.34	4.6	6.84	1.9	451.	0.99	1.4
		P35	1		7	1	74	5	2	2				4		6					4		9	
A1	A		4.3	4	337.	10	172.	1.0	0.1	1.8	12.9	2.29	4.1	15.1	15.1	44.	4.95	8.96	8.9	4.37	2	374.	1.87	0.5
		P36	5		4	9	77	9	7	1				9		1					8		1	
A1	A		4.6	4.2	324.	11	200.	1.1	0.2	0.8	10.7	2.56	3.42	13.2	19.3	25.	6.58	7.04	9.2	4.6	1.2	392.	0.99	1.0
		P39	9	7	5	5	65	7	2	6				6		1					6		9	
A1	A		4.5	4.0	940	12	208.	0.9	0.2	1.0	11.6	2.35	3.4	13.9	16.8	30.	6.5	4.48	14.2	17.4	1.8	406	3.42	1.9
		P40	7	9		4	48	3		5				5		9				8		2		
A1	A		4.4	3.7	666.	19	251.	1.5	0.5	2.2	23.3	3.74	6.03	27.0	13.8	38	4.04	35.82	11.5	3.39	2.1	222.	2.51	2.4
		P41	8	9	1	1	56	9	7	9				4							2		9	
A1	A		3.9	3.7	288.	11	192.	2.0	0.7	3.7	25.1	3.99	7.7	29.0	13.7	48.	2.88	31.99	3	2.42	1.7	278.	1.88	1.4
		P42	2	9	2	5	82	8	8	1				9		2					4		6	
A1	A		4.2	4.2	222.	72	121.	1.2	0.2	1.1	17	2.14	3.28	19.1	11.2	34.	2.77	15.99	2.2	9.04	0.6	387.	0.66	0.9
		P43	7	2	2		86	2	1	4				4		8					9		4	
A1	A		4.5	4.0	119.	81	157.	1.1	0.5	1.7	7.9	2.64	4.35	10.5	25	39.	6.48	3.84	17.8	2.79	2.9	282.	0.66	0.2
		P44	2	5	7		11	9	6	1				4		3					8		6	
A1	B		4.5	4.2	156.	70	184.	1.4	0.5	1.3	16.2	2.96	4.29	19.1	15.4	31	4.19	10.24	2.7	4.96	1.6	338	0.73	0.5
		P45	8	5	3		52	5	3	3				6									3	
A1	A		4.2	4.1	279.	81	188.	1.1	0.3	1.7	14.9	2.5	4.21	17.4	14.4	40.	4.71	11.51	3.9	5.46	0.9	281	0.47	0.5
		P46	5	4	2		44	7		1						6							5	
A1	A		4.4	4.0	263.	12	282.	1.4	0.4	1.8	17.1	3.44	5.25	20.5	16.7	34.	5.99	14.07	4.9	5.12	1.2	300	0.82	0.8
		P47	9	8	5	4	89	2	7	1				4		5							4	
A1	B		4.3	4.1	123.	91	228.	1.6	0.6	1.5	18.7	3.51	5.03	22.2	15.8	30.	4.46	16.63	1.5	6.73	1.6	222.	1.51	0.9
		P48	8	6	5		07	9		2				1		2					6		3	
A1	A		5.2	4.1	206.	10	204.	2.2	0.8	1.6	17.9	4.19	5.81	22.0	19	27.	4.03	11.51	4.3	7.77	10.	450.	1.19	0.9
		P56	8	7	9	3	57	1	3	2				9		9				8	8		9	
A1	B		4.6	4.1	131.	97	186.	1.6	0.4	2.1	21.4	3.14	5.33	24.5	12.8	41.	3.3	12.15	2.5	7.28	6.8	418	0.78	0.7
		P57			1		48	3	5	9				4		1							6	
A1	B	P58	4.8	4.1	261.	85	188.	1.1	0.3	1.2	15.2	2.47	3.71	17.6	14	33.	4.64	8.32	10.6	4.67	0.9	317.	0.51	0.6

			3	7	5		44	3		4				7		4					4		6	
A1	B	P59	5.3	4.2	279.	10	228.	1.7	0.5	1.3	18.7	3.53	4.86	22.2	15.9	27.	4.46	17.91	2	12.9	5	313.	1.19	0.8
				2	2	7	07	2	4	3				3		4				6		7		0
A1	A	P62	4.6	4.1	228.	83	184.	1.3	0.3	1.7	16.7	2.76	4.47	19.4	14.2	38.	4.12	9.6	5.2	5.78	6.4	342	0.95	0.8
				9	5	6		52	8	6	1				6		3							0
A1	B	P64	4.7	4.1	149.	11	247.	2.0	0.8	1.6	17.1	4.32	5.94	21.4	20.2	27.	5.03	16.63	3.9	3.97	3	280.	2.72	0.9
				7		3	1	65	8	8	2				2		3						7	
A1	B	P65	6.1	4.6	452.	14	275.	2.3	0.9	0.1	7.4	4.87	5.06	12.2	39.7	3.8	9.75	3.2	13.1	13.6	24.	425.	2.51	0.3
					7	8	4	06	2	8	9				7							8	3	
A1	B	P66	5.7	4.7	182.	19	333.	2.5	1.3	0	3.1	5.79	5.79	8.89	65.1	0	16.3	4.48	30.1	7.59	32.	362.	2.63	0.4
				9	4	7	1	8	4	1								3				2	7	
A1	B	P67	4.7	4.2	126.	95	208.	1.1	0.3	0.8	6.1	2.71	3.57	8.81	30.8	24.	10.2	4.16	20.1	3.48	1.1	241.	0.68	0.1
				9	5	8		48	9	7	6						1	9					7	
A1	B	P68	4.8	4.4	129.	93	224.	1.2	0.4	0.4	9.6	2.91	3.39	12.5	23.3	14.	7.79	10.24	7.3	6.11	2.2	348.	1.16	0.6
				8	4	4		15	7	3	8				1		2						4	
A1	A	P69	5.9	4.5	247.	10	239.	2.4	1.3	0.3	10.4	5.11	5.49	15.5	32.9	6.9	6.72	7.68	8.3	6.08	10.	366.	0.73	0.4
				3		2	5	81	9	1	8				1							7	5	
A1	A	P70	5.3	4.3	124.	91	231.	2.3	0.8	0.7	13.5	4.42	5.18	17.9	24.7	14.	5.63	14.71	4.8	5.08	6.2	388.	1.61	0.7
				9	5	7		98	1	7	6				2		7						6	
A1	B	P71	4.5	4.1	141.	97	228.	1.4	0.4	1.3	14.1	3.15	4.48	17.2	18.3	29.	5.75	14.71	4.3	3.07	1.6	238	0.99	0.8
					7	1		07	5	6	3				5		7							
A1	B	P72	5.4	4.3	92.9	83	224.	2.9	1.4	0.6	13.5	5.54	6.21	19.0	29.1	10.	5.12	14.71	4.1	3.98	3.6	292.	1.2	0.7
				8	7			15	2	3	7				4		8						8	
A2	B	P73	5.3	4.5	197.	87	182.	1.3	0.4	0.2	7.1	2.82	3.11	9.92	28.4	9.3	8	4.48	9.8	5.65	3.4	346.	0.54	0.4
				1	5	8		56	3	7	9												2	
A2	B	P74	4.6	4.0	59.8	16	271.	3.1	1.7	2.3	23.3	6.45	8.83	29.7	21.7	27	3.96	31.99	2.3	2.19	4.4	320.	2.65	1.6
				5	2		9	14	1	3	8				5							2		9
A2	B	P75	4.5	4.0	179.	11	216.	1.7	0.7	2.8	26.7	3.73	6.59	30.4	12.3	43.	3.09	15.35	1.3	5.55	2.5	273.	1.64	1.5
				9	4	6	5	32	9		6				3		4					2		2
A2	B	P77	5.0	4.1	242.	12	251.	1.7	0.5	1.1	13.7	3.67	4.81	17.3	21.1	23.	6.3	12.79	6.2	7.14	2.3	357.	1.89	1.0
				2	7	5	8	56	1	4	4				7		7					5		3
A2	B	P78	5.8	4.5	280.	18	353.	2.3	1.1	0.1	4.6	5.49	5.68	10.0	54.4	3.3	15.2	6.4	29.4	7.87	13.	294.	2.52	0.2
				5	5	2	5	38		8	9				9			3				1	8	
A2	B	P79	6.2	4.9	128.	17	298.	2.9	1.2	0	2.4	5.9	5.9	8.3	71.1	0	15.6	3.2	32	6.29	18.	473	3.23	0.2
				4	6	1	5	55		5								4				5		5
A2	B	P80	6.2	4.9	107	10	216.	2.8	1.2	0	6.4	5.27	5.27	11.6	45.2	0	8.06	6.4	6.5	8.48	14.	311.	1.99	0.4
				6	6		5	32	2	4					7							7	1	
A2	B	P81	6.2	4.8	77.9	13	275.	2.7	1.2	0	4.4	5.55	5.55	9.95	55.8	0	12.0	4.8	13.5	5.17	8.2	249.	1.61	0.3
					7		8	06	6	4								2					8	
A2	A	P82	5.5	4.5	330.	18	361.	3.4	1.6	0.2	7.1	7.06	7.35	14.1	49.9	3.9	11.0	7.68	16.5	7.41	27.	850.	5.33	0.4
				3	8	9	9	21		9					6			9				8	1	
A2	A	P83	5.1	4.1	269.	13	263.	1.7	0.5	1.1	13.8	3.74	4.88	17.5	21.3	23.	6.53	12.79	7.9	7.79	2.3	400.	2.01	0.5
					7	3	4	31	3	2	4				4			4					7	
A2	A	P84	4.4	4.0	321.	12	220.	1.2	0.2	1.4	14.1	2.86	4.29	16.9	16.9	33.	5.65	12.15	7.1	5.86	1.3	320.	1.21	0.8

			2	9	3	4	23	9	9	3				6	3					2	3			
A2	A	P85	4.7	3.8	84.7	18	243.	2.9	1.3	4.9	39.9	5.79	10.7	45.6	12.7	46.	2.32	35.82	0.7	4.4	2.6	446.	1.81	1.4
			2			5	73	1	5	5			4	9	1					8			0	
A2	B	P86	4.3	3.7	145.	12	186.	1.6	0.8	3.7	30.3	3.6	7.31	33.9	10.6	50.	2.4	20.91	2.8	4.73	2.2	449.	1.62	1.2
			9	9	2	7	97	5	1	1					8					2			0	
A2	B	P87	4.7	3.9	88	14	188.	2.6	1.5	3.5	31.9	5.33	8.85	37.2	14.3	39.	2.21	30.42	0.4	4.31	3.3	301.	2.21	1.4
			4			1	94	1	4	2				3		8					7			6
A2	A	P88	4.8	3.8	250.	12	255.	1.8	1.3	2.7	26.6	4.57	7.33	31.1	14.7	37.	3.57	26.61	5.7	9	4.8	443.	1.6	1.3
			3	7	3	79	4		4	6				7		7					8			0
A2	A	P89	4.3	3.8	124	13	283.	1.7	1.1	3.6	28.4	4.53	8.15	32.9	13.8	44.	3.74	27.25	2	8.42	2.5	435.	2.26	1.7
			8	6		5	36	6	9	2				3		4					5			5
A2	B	P90	4.0	3.6	400.	15	442.	1.3	0.8	3.7	33.8	4.45	8.16	38.2	11.6	45.	5.03	32.32	7.2	6.04	1.5	408.	1.2	1.5
			2	9	3	4	57	1	2	1				5		5					1			7
A2	B	P91	5.0	4.2	350.	13	243.	3	1.3	5.2	41.6	5.77	11.0	47.3	12.2	47.	2.24	41.82	1.3	2.2	3.5	258	4.6	1.5
			5	5	8	3	98		7	4				1		6								4
A2	B	P92	5.0	4.1	170.	11	291.	4.9	2.8	3.0	34.3	9.34	12.3	43.6	21.4	24.	2.9	47.53	0.1	1.7	6.1	169.	7.81	1.7
			5	7	9	1	23	8	1	5				9		4					2			2
A2	B	P93	4.6	3.9	110.	14	279.	2.9	1.9	2.4	36.8	6.53	9.01	43.3	15.1	27.	2.8	59.56	0.5	4.05	3.8	218.	3.65	1.4
			1	3	9	42	6	7	8					3		5					9			3
A2	B	P94	5.3	4.3	166.	99	185	1.5	0.6	0.6	21.5	3.21	3.88	24.7	13	17.	3.26	13.31	3.2	11.5	5.2	318.	1.57	0.5
			5	5	4			4	1	7				1		3				1		5		7
A2	B	P95	5.0	3.8	662	18	243.	1.4	0.8	2.2	21.1	3.83	6.12	24.9	15.4	37.	4.26	9.82	14.6	13.4	2.6	434.	2.6	0.5
			2	2		6	98	6	3	9				3		4				4		3		1
A2	B	P96	4.6	4.0	115.	11	173.	1.4	0.8	2	19.8	3.34	5.34	23.1	14.4	37.	3.25	16.48	3	4.35	7.4	427.	1.11	0.9
			9	8	8	5	18	1	8					4		5					9			7
A2	B	P97	4.4	4	153.	17	310.	1.9	0.8	1.7	14	4.52	6.23	18.5	24.4	27.	7.3	16.48	5.7	3.69	2.3	340.	1.85	0.8
			4		5	8	92	1		1				2		4					8			1
A2	B	P98	4.7	3.6	406.	26	373.	1.1	0.6	2.2	20.1	4.08	6.37	24.1	16.9	35.	6.72	17.11	15	3.81	0.9	162.	1.3	1.0
			9	7	3	5	93	2	5	9				8		9					2			0
A2	B	P99	4.8	4.1	220.	93	169.	1.1	0.4	1.5	16.3	2.6	4.12	18.9	13.8	36.	3.89	14.57	4.2	5.59	1.5	263	1.37	0.9
			4				25	9	4	2						9								3
A2	B	P10	5.0	4.1	279.	77	153.	1.3	0.7	1.2	13	2.96	4.2	15.9	18.5	29.	4.18	6.02	10.7	6.28	4.1	481	0.79	0.3
		0	2	2	7		49	7	3	4				6		5								3
A3	B	P10	5.2	3.9	241.	67	102.	0.7	0.4	1.5	11.9	1.82	3.34	13.7	13.3	45.	3.24	4.75	16	3.07	0.9	501.	0.47	0.2
		1	5	9	3		3	4	6	2				2		5					4			3
A3	B	P10	4.9	4.1	502.	10	212.	1.7	0.8	1.0	14.3	3.82	4.87	18.1	21.1	21.	5.1	9.51	10	4.81	13.	381.	5.59	0.4
		3	6		8	1	47	9	5	5				2		6					8			5
A3	B	P10	5.1	4.2	223.	83	192.	1.7	0.9	0.7	11.3	3.75	4.51	15.0	24.9	16.	5.57	7.6	6.9	6.86	5.8	436.	1.28	0.3
		4	9	5	5		78	3	7	6				5		9					2			8
A3	B	P10	5.1	4.1	261.	91	163.	1.2	0.6	1.2	13.4	2.8	4.04	16.2	17.3	30.	4.38	12.67	6.6	5.24	2	433.	0.92	0.5
		5		5	9		34	4	2	4						7					4			1
A3	B	P10	4.5	4	104	12	271.	3.1	1.9	2.4	22.6	6.56	9.04	29.1	22.5	27.	4.05	36.75	2	5.18	4.2	291.	2.38	1.6
		6	4			9	54		5	8				6		4					6			9
A3	B	P10	4.6	3.9	82.2	15	208.	2.9	2.1	3.0	28.6	6.39	9.44	34.9	18.3	32.	2.59	35.49	2.8	3.56	2.7	426.	1.74	1.4

		7	7		0	53	3	7	5					9	3						2		6	
A3	B	P10	4.8	4.0	156.	69	131.	1.9	1.3	2.1	19.5	3.98	6.08	23.4	17	34.	2.44	19.01	3.2	3.81	1.5	484.	0.9	0.6
		8	1	7	8		83		3					8		5					6		8	
A3	B	P10	4.8	4.0	168.	10	196.	1.8	1.2	1.9	15.7	4.25	6.15	19.9	21.3	30.	4.29	13.31	7.8	3.07	4.1	376.	1.49	0.5
		9	2	7	4	7	72	5	7					5		9					8		1	
A3	B	P11	4.7	3.7	247.	14	251.	3.3	2.1	2.9	27.2	6.98	9.93	34.1	20.4	29.	3.2	40.55	6.9	2.7	4.5	224.	6.09	1.7
		0	7	3	3	7	85	9	2	5				8		7					8		7	
A3	B	P11	4.3	3.7	222.	13	200.	2.9	1.4	3.2	30.2	5.66	8.9	35.8	15.8	36.	2.43	38.02	3.9	3.82	4	343.	4.72	1.7
		2	3	5	3	5	66	5	9	4				6		4					8		5	
A3	B	P11	4.7	3.9	185.	11	186.	2.2	1.5	3.2	24.7	4.85	8.09	29.5	16.4	40	2.75	29.15	1.7	4.2	1.6	163.	1.37	0.8
		4	5	8	8	7	97	4		4				5							2		3	
A3	B	P11	4.2	3.9	575.	14	283.	3.4	1.7	2.6	30.5	6.78	9.45	37.2	18.2	28.	3.3	45.62	4.4	8.15	5.8	165.	8.81	1.4
		5	7	1	9	3	36	7	1	7				8		3					8		9	
A3	B	P11	4.2	3.9	303.	20	216.	3.5	1.9	2.3	24.5	7	9.38	31.5	22.2	25.	2.99	32.32	3.6	5.44	5	218.	6.28	1.4
		6	4	5	8	6	41	5	8	8						4					2		0	
A3	B	P11	4.6	3.9	195.	14	224.	2.9	1.8	2.3	25.1	6.22	8.6	31.3	19.9	27.	3.11	24.08	1.7	5.16	3.6	242.	3.05	1.2
		7	7	8	3	1	29	9	9	8				2		7					9		3	
A3	B	P11	4.6	4	203.	10	188.	1.6	0.7	2.2	21.2	3.5	5.79	24.7	14.2	39.	3.33	22.18	2.6	4.19	3.7	334.	1.62	0.7
		8	3		1	7	94	5	5	9						6					7		8	
A3	A	P11	4.7	3.6	1126	23	362.	2.7	1.0	2.6	31.1	5.94	8.61	37.0	16	31	4.25	27.88	11.7	10.8	4.7	233.	11.0	1.0
		9	4	6	.7	8	12	3	3	7				4					3		8	5	6	
A3	B	P12	5.6	4.3	265.	93	224.	1.6	0.6	0.5	10.4	3.46	4.03	13.8	25	14.	7.04	6.97	8.1	6.5	40.	342.	3.3	0.3
		0	7	5	5		29	2	3	7				6		1					4	6	3	
A3	B	P12	5.4	4.2	161.	87	192.	1.2	0.4	1.0	13.5	2.76	3.81	16.2	17	27.	5.15	10.14	3.6	3.05	11.	427.	1.09	0.4
		1	2	4	1		78	1	9	5				6		6					3	3	8	

*Environment.

pH: active acidity (H₂O); P: phosphorus; Na: sodium (extractor Mehlich 1); Ca: calcium; Mg: magnesium; H+Al: total acidity (extractor calcium acetate 0,5 mol L⁻¹ pH 7,0); BS: bases sum; CECeff: effective cation exchange capacity; CECT: total cation exchange capacity pH 7.0; V: saturation of bases; m: aluminum saturation index; OM: organic matter; Fe: iron; N: total nitrogen.

Table 2. Soil physical properties of the rocky outcrops from Harmony Point – Nelson Island.

Rocky Outcrop	Environment	Plot	Coarse sand	Fine sand	Silt	Clay	Class	Soil type
Kg/kg								
A1	B	P1	0.15	0.39	0.22	0.23	Sandy clay loam	2
A1	B	P2	0.34	0.19	0.25	0.20	Sandy clay loam	2
A1	B	P3	0.36	0.21	0.22	0.19	Sandy loam	2
A1	B	P4	0.30	0.29	0.19	0.20	Sandy clay loam	2

A1	B	P5	0.33	0.26	0.20	0.19	Sandy loam	2
A1	B	P6	0.20	0.26	0.24	0.23	Sandy clay loam	2
A1	B	P7	0.28	0.34	0.20	0.16	Sandy loam	2
A1	B	P8	0.24	0.34	0.20	0.20	Sandy clay loam	2
A1	B	P9	0.25	0.21	0.23	0.29	Sandy clay loam	2
A1	B	P10	0.33	0.25	0.20	0.21	Sandy clay loam	2
A1	B	P12	0.23	0.35	0.19	0.22	Sandy clay loam	2
A1	B	P14	0.14	0.27	0.30	0.27	Sandy loam	2
A1	B	P15	0.26	0.23	0.25	0.24	Sandy clay loam	2
A1	B	P16	0.32	0.25	0.24	0.17	Sandy loam	2
A1	B	P18	0.33	0.25	0.20	0.21	Sandy clay loam	2
A1	A	P20	0.34	0.24	0.20	0.20	Sandy clay loam	2
A1	B	P21	0.33	0.25	0.20	0.21	Sandy clay loam	2
A1	A	P22	0.33	0.27	0.15	0.23	Sandy clay loam	2
A1	A	P23	0.23	0.25	0.35	0.15	Loam	2
A1	B	P24	0.26	0.37	0.23	0.12	Sandy loam	1
A1	B	P25	0.28	0.24	0.28	0.19	Sandy loam	2
A1	A	P28	0.33	0.21	0.20	0.24	Sandy clay loam	2
A1	B	P31	0.33	0.25	0.20	0.21	Sandy clay loam	2
A1	B	P32	0.36	0.23	0.18	0.21	Sandy clay loam	2
A1	B	P33	0.35	0.30	0.17	0.17	Sandy loam	2
A1	B	P34	0.28	0.23	0.24	0.23	Sandy clay loam	2
A1	A	P35	0.34	0.24	0.20	0.20	Sandy clay loam	2
A1	A	P36	0.31	0.31	0.19	0.18	Sandy loam	2
A1	A	P39	0.29	0.21	0.23	0.26	Sandy clay loam	2
A1	A	P40	0.34	0.24	0.20	0.20	Sandy clay loam	2
A1	A	P41	0.19	0.26	0.22	0.30	Sandy clay loam	2
A1	A	P42	0.34	0.24	0.20	0.20	Sandy clay loam	2
A1	A	P43	0.18	0.32	0.26	0.21	Sandy clay loam	2
A1	A	P44	0.59	0.09	0.13	0.17	Sandy loam	1
A1	B	P45	0.32	0.30	0.15	0.22	Sandy clay loam	2
A1	A	P46	0.44	0.16	0.17	0.21	Sandy clay loam	2
A1	A	P47	0.49	0.15	0.12	0.22	Sandy clay loam	2

A1	B	P48	0.37	0.20	0.15	0.26	Sandy clay loam	2
A1	A	P56	0.29	0.27	0.19	0.23	Sandy clay loam	2
A1	B	P57	0.34	0.25	0.18	0.21	Sandy clay loam	2
A1	B	P58	0.64	0.13	0.07	0.15	Sandy loam	1
A1	B	P59	0.20	0.21	0.33	0.22	Loam	2
A1	A	P62	0.38	0.21	0.18	0.21	Sandy clay loam	2
A1	B	P64	0.27	0.29	0.19	0.24	Sandy clay loam	2
A1	B	P65	0.31	0.30	0.24	0.14	Sandy loam	1
A1	B	P66	0.21	0.43	0.27	0.08	Sandy loam	1
A1	B	P67	0.55	0.14	0.15	0.14	Sandy loam	1
A1	B	P68	0.25	0.34	0.23	0.16	Sandy loam	2
A1	A	P69	0.45	0.18	0.17	0.18	Sandy loam	2
A1	A	P70	0.24	0.28	0.24	0.22	Sandy clay loam	2
A1	B	P71	0.23	0.25	0.27	0.22	Sandy clay loam	2
A1	B	P72	0.27	0.29	0.20	0.22	Sandy clay loam	2
A2	B	P73	0.33	0.32	0.18	0.15	Sandy loam	1
A2	B	P74	0.17	0.33	0.23	0.26	Sandy clay loam	2
A2	B	P75	0.36	0.19	0.21	0.22	Sandy clay loam	2
A2	B	P77	0.44	0.23	0.15	0.16	Sandy loam	1
A2	B	P78	0.26	0.38	0.20	0.13	Sandy loam	1
A2	B	P79	0.30	0.38	0.16	0.14	Sandy loam	1
A2	B	P80	0.32	0.27	0.22	0.17	Sandy loam	2
A2	B	P81	0.35	0.21	0.27	0.16	Sandy loam	2
A2	A	P82	0.27	0.28	0.27	0.17	Sandy loam	2
A2	A	P83	0.26	0.33	0.14	0.26	Sandy clay loam	2
A2	A	P84	0.28	0.30	0.17	0.23	Sandy clay loam	2
A2	A	P85	0.34	0.24	0.20	0.20	Sandy clay loam	2
A2	B	P86	0.36	0.16	0.20	0.26	Sandy clay loam	2
A2	B	P87	0.33	0.25	0.20	0.21	Sandy clay loam	2
A2	A	P88	0.40	0.18	0.14	0.25	Sandy clay loam	2
A2	A	P89	0.34	0.24	0.20	0.20	Sandy clay loam	2
A2	B	P90	0.30	0.24	0.17	0.27	Sandy clay loam	2
A2	B	P91	0.33	0.25	0.20	0.21	Sandy clay loam	2

A2	B	P92	0.33	0.25	0.20	0.21	Sandy clay loam	2
A2	B	P93	0.33	0.25	0.20	0.21	Sandy clay loam	2
A2	B	P94	0.28	0.25	0.23	0.21	Sandy clay loam	2
A2	B	P95	0.47	0.14	0.15	0.22	Sandy clay loam	2
A2	B	P96	0.36	0.24	0.17	0.22	Sandy clay loam	2
A2	B	P97	0.22	0.24	0.33	0.20	Loam	2
A2	B	P98	0.40	0.20	0.17	0.21	Sandy clay loam	2
A2	B	P99	0.38	0.20	0.19	0.21	Sandy clay loam	2
A2	B	P100	0.48	0.17	0.13	0.20	Sandy clay loam	2
A3	B	P101	0.64	0.10	0.10	0.15	Sandy loam	1
A3	B	P103	0.30	0.25	0.23	0.20	Sandy clay loam	2
A3	B	P104	0.39	0.22	0.18	0.20	Sandy clay loam	2
A3	B	P105	0.38	0.22	0.19	0.20	Sandy clay loam	2
A3	B	P106	0.33	0.25	0.20	0.21	Sandy clay loam	2
A3	B	P107	0.33	0.25	0.20	0.21	Sandy clay loam	2
A3	B	P108	0.48	0.18	0.14	0.19	Sandy loam	2
A3	B	P109	0.39	0.23	0.15	0.21	Sandy clay loam	2
A3	B	P110	0.33	0.25	0.20	0.21	Sandy clay loam	2
A3	B	P112	0.33	0.25	0.20	0.21	Sandy clay loam	2
A3	B	P114	0.46	0.14	0.18	0.20	Sandy clay loam	2
A3	B	P115	0.17	0.20	0.33	0.28	Sandy loam	2
A3	B	P116	0.33	0.25	0.20	0.21	Sandy clay loam	2
A3	B	P117	0.32	0.18	0.20	0.28	Sandy clay loam	2
A3	B	P118	0.29	0.28	0.20	0.21	Sandy clay loam	2
A3	A	P119	0.29	0.18	0.24	0.27	Sandy clay loam	2
A3	B	P120	0.41	0.22	0.18	0.17	Sandy loam	2
A3	B	P121	0.25	0.30	0.23	0.20	Sandy clay loam	2

3. 2 ROCKY OUTCROPS CHARACTERIZATION: ENVIRONMENT AND SPECIES RICHNESS PATTERN

The rocky formations, with the apparent difference in sizes and plant covers, were mapped through drone images (Fig. 6) and by the phytosociology method (Fig. 7d, h, j). Harmony Point is a region with extensive plant formation. From the total of 121 plots analyzed we found 44 species divided into 14 families and 30 lichens species, 8 families and 12 mosses species, one macroalgae, and one cyanobacteria. One sterile lichen species and cyanobacteria were not possible to identify (Table 3). We counted and identified the moss species with gametophytes, to provide the total cover of specie in the plot.

The three rocky outcrops share 11 species in common, while some species have occurrences restricted to only one rocky outcrop. The A1 site presents ten different species from the other areas, while A2 has three, and A3 presents 2 species (Fig. 8a).

Outcrop A1 was the most extensive, with 116 meters in length (Fig. 6a; 7a) and 72 plots were used to cover all rock fragments. Various nest marks the Giant-petrel's presence, occurring pairs and their chicks (Fig.7c), modifying the color of the top landscape and with vegetation practically absent. With 38 species (Table 3) the moss *Sanionia uncinata* Loeske was the most frequent, followed by the moss *Andreaeae gainii* Card (Table S4). The *S. uncinata* carpet covers the adjacencies (Fig. 7b, d), however, the species was found inside the fragment. The lichen *Acarospora macrocyclos* Vain. and one unidentified lichen provided a dark color to the rocks along with *A. gainii* (Fig. 6b). Despite the moss presenting higher relative frequency, the lichens were more representative in species numbers, with 28 lichens species contrasting with 9 mosses and the macroalgae *Prasila crispa* (Lightfoot) Menegh.

With 61 meters in length, outcrop A2 (Fig. 6b; 7e) was covered with 28 plots and presented 24 species. The moss *S. uncinata* was the most frequent, followed by the lichen *Cladonia borealis* S. Stenroos (Fig. 7f) (Table S5). Despite being less extensive, this rocky outcrop showed many Giant-petrel nests too (Fig. 7g). The same pattern about cover and frequency was observed here. Despite the moss carpet dominance, the lichens presented higher number of species, with 15 species and seven mosses (Fig. 7h). It was found also one macroalgae and one species of cyanobacteria. In the surrounding of the outcrop, there is a large cushion of *Chorisodontium aciphyllum* Brotherus, registered just in this outcrop.

utcrop A3 was shorter in length, with 36 meters in length (Fig. 6c; 7i). It was analyzed with 21 phytosociology plots, resulting in 20 plant species. The *S. uncinata* moss carpet

showed the higher cover but presented the similar species *Sanionia georgicouncinata* Ochyra with a higher frequency (Fig. 7j) (Table S6). Species diversity was dominated by lichens, with 10 species, five mosses, and one macroalgae (Fig. 7k, l).

The environments were divided into two classes. Environment A is the phytosociology plots that represent rock substrate, and presented 32 species, while B is the plots that represent bare soil, with 36 species (Table 3). When compared both, they shared the occurrence of 22 species, while 10 species occurred only on the rocky substrate, with nine lichens and two mosses. While the bare soil had 12 with restricted occurrence, being seven lichens, four mosses, and cyanobacteria (Fig. 8b).

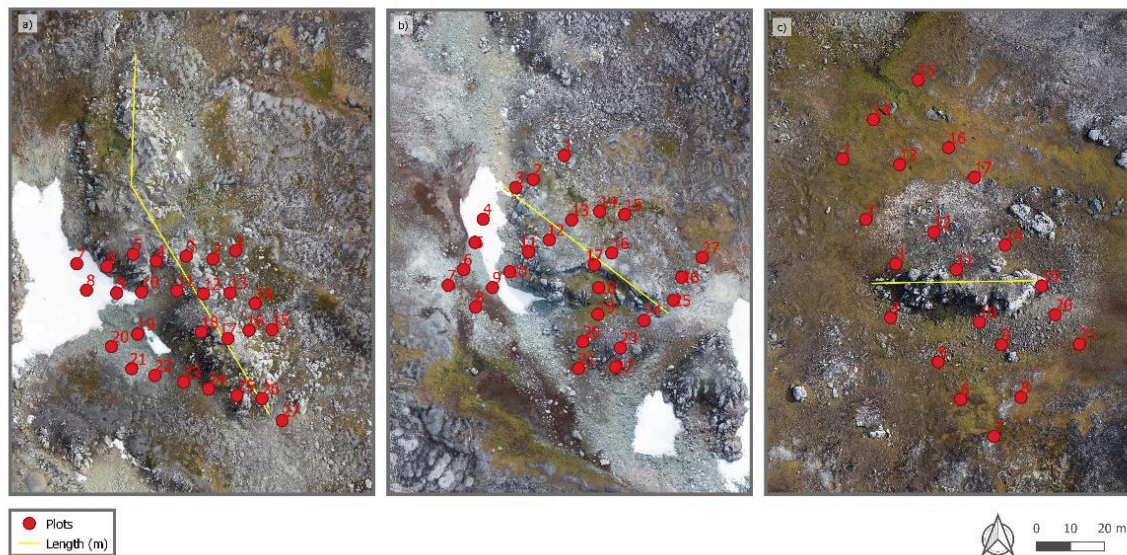


Figure 6. Three rocky outcrops were analyzed through phytosociology and soil plots and area length measurements. a) Rocky outcrop A1; b) Rocky outcrop A2; and c) Rocky outcrop A3.

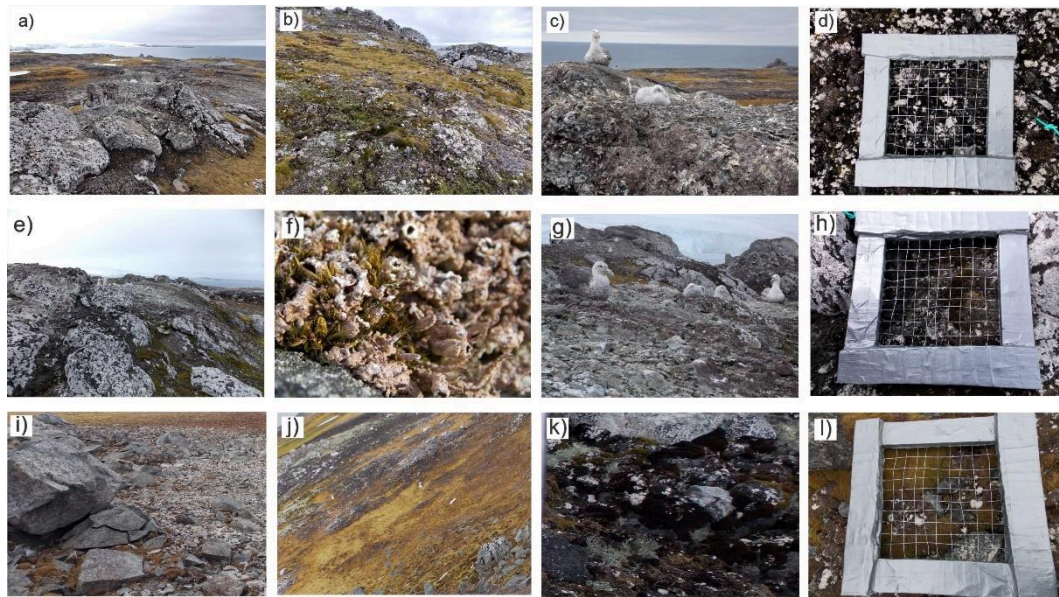
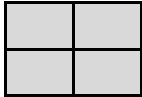
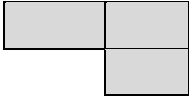
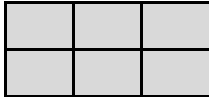
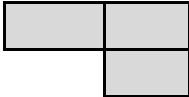
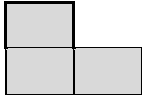
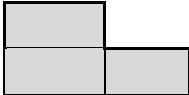
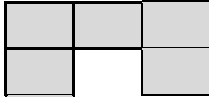
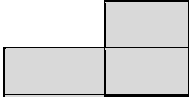
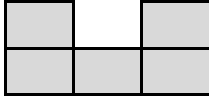
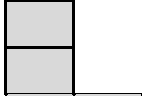
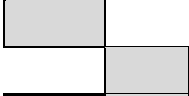
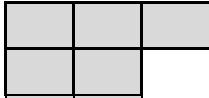
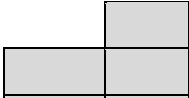
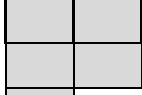
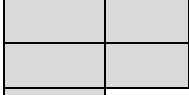


Figure 7. Rocky outcrops and their distinct cover. a) Rocky outcrop A1, b) their vegetation surrounded, c) with Giant-petrel presence, and d) square dominated by *Andreaea gainii* and *Acarospora macrocyclos*. e) Rocky outcrop A2 f) dominated by *Cladonia borealis* lichen, with g) Giant-petrel presence and h) their square plot; i) Rocky outcrop A3 j) with *Sanionia* spp., k) *Andreaea* spp., and l) the square plot representative.

Table 3. Plant species occurrence in three rocky outcrops and two different environments (substrates): rock (A) and bare soil (B).

Group	Family	Species	Rocky outcrop			Environment	
			A1	A2	A3	A	B
Algae							
	Prasiolaceae						
		<i>Prasiola crispa</i> (Lightfoot) Menegh.					
Bryophyta							
	Andreaeaceae						
		<i>Andreaea gainii</i> Card.					
		<i>Andreaea regularis</i> Müll. Hal.					
	Amblystegiaceae						
		<i>Sanionia georgicouncinata</i> Ochyra					
		<i>Sanionia uncinata</i> Loeske					
		<i>Warnstorfia sarmentosa</i> (Wahlenb.) Hedenäs					
	Bryaceae						
		<i>Bryum archangelicum</i> Bruch & Schimp.					
	Dicranaceae						
		<i>Chorisodontium aciphyllum</i> Brotherus					
	Bartramiaceae						
		<i>Conostomum magellanicum</i> Sull.					
	Mielichhoferiaceae						
		<i>Pohlia drummondii</i> (Müller Hal.) A. L. Andrews					

Polytrichaceae			
<i>Polytrichastrum alpinum</i> Hedw.			
<i>Polytrichum juniperinum</i> Hedwig			
Sphaerophoraceae			
<i>Syntrichia princeps</i> Mitten			
Cyanophyta			
-			
Unidentified cyanobacteria			
Lichenized and lichenicolous fungi			
Acarosporaceae			
<i>Acarospora macrocyclos</i> Vain.			
Catillariaceae			
<i>Catillaria corymbosa</i>			
Cladoniaceae			
<i>Cladonia borealis</i> S. Stenroos			
<i>Cystocoleus niger</i> (Huds.) Hari			
Haematommataceae			
<i>Haematomma erythromma</i> (Nyl.) Zahlbr.			
<i>Henediella heimii</i> Zander			
Lecanoraceae			
<i>Carbonea assentiens</i> (Nyl.) Hertel			
<i>Huea cerussata</i> (Hue) C.W. Dodge & G.E. Baker			
<i>Rhizoplaca aspidophora</i> (Vain.) Redón			
Ochrolechiaceae			
<i>Ochrolechia antarctica</i> (Müll. Arg.) Darb.			
<i>Ochrolechia frigida</i> (Sw.) Lynge			
Pannariaceae			
<i>Pannaria hookeri</i> (borre rex Sm.) Nyl.			
<i>Psoroma cinnamomeum</i> Malme			
<i>Psoroma hypnorum</i> (Vahl) Grey			
Parmeliaceae			
<i>Himantormia lugubris</i> (Hue) I. M. Lamb			
<i>Microglaena antarctica</i> IM Lamb			
<i>Usnea aurantiaco-atra</i> (Jacq.) Bory			
<i>Usnea antarctica</i> Du Rietz			
Physciaceae			
<i>Buellia anisomera</i> Vain.			
<i>Buellia latemarginata</i> Darb.			

<i>Physconia muscigena</i> (Ach.) Poelt		
Ramalinaceae		
<i>Lecania brialmontii</i> (Vain.) Zahlbr.		
Rhizocarpaceae		
<i>Rhizocarpon griseolum</i> (Hue) Darb.		
<i>Rinodina petermannii</i> (Hue) Darb.		
Stereocaulaceae		
<i>Stereocaulon alpinum</i> Lauren ex Funck		
<i>Stereocaulon glabrum</i> (Müll. Arg.) Vain.		
Teloschistaceae		
<i>Caloplaca regalis</i> (Vain.) Zahlbr.		
Verrucariaceae		
<i>Mastodiaa tessellata</i> Hook. f & Harvey		
<i>Verrucaria antarctica</i> C.W.Dodge		
-		
Unidentified lichen		

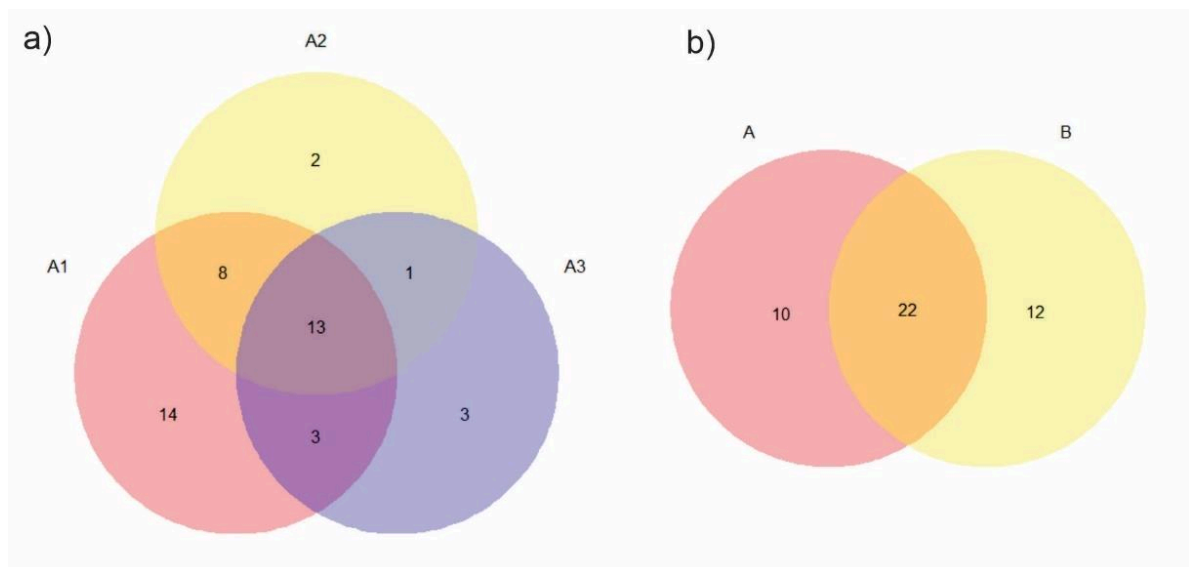


Figure 8. Venn diagram showing the similarities and dissimilarities of species that occurred in the three rocky outcrops (a) and when separated into two environments (b).

We observed similar richness patterns among the rocky outcrop A3 and A2, and A2 with A1. According to rarefaction, A3 does not overlap with A1, probably due to the low number of species. The rarefaction curves indicated the sampling sufficiency, with a greater sampling effort, and tend to stabilize with extrapolation (Fig. 9a). The NMDS (Fig. 9b) showed that species composition varied from rocky outcrops ($F_{1,16} = 4.25$, PERMANOVA: $p = 0.001$),

however, tends to concentrate in A2. The Stress-Euclidean showed that they were efficient (Stress = 0.18) based on the likelihood fit of Euclidean distance.

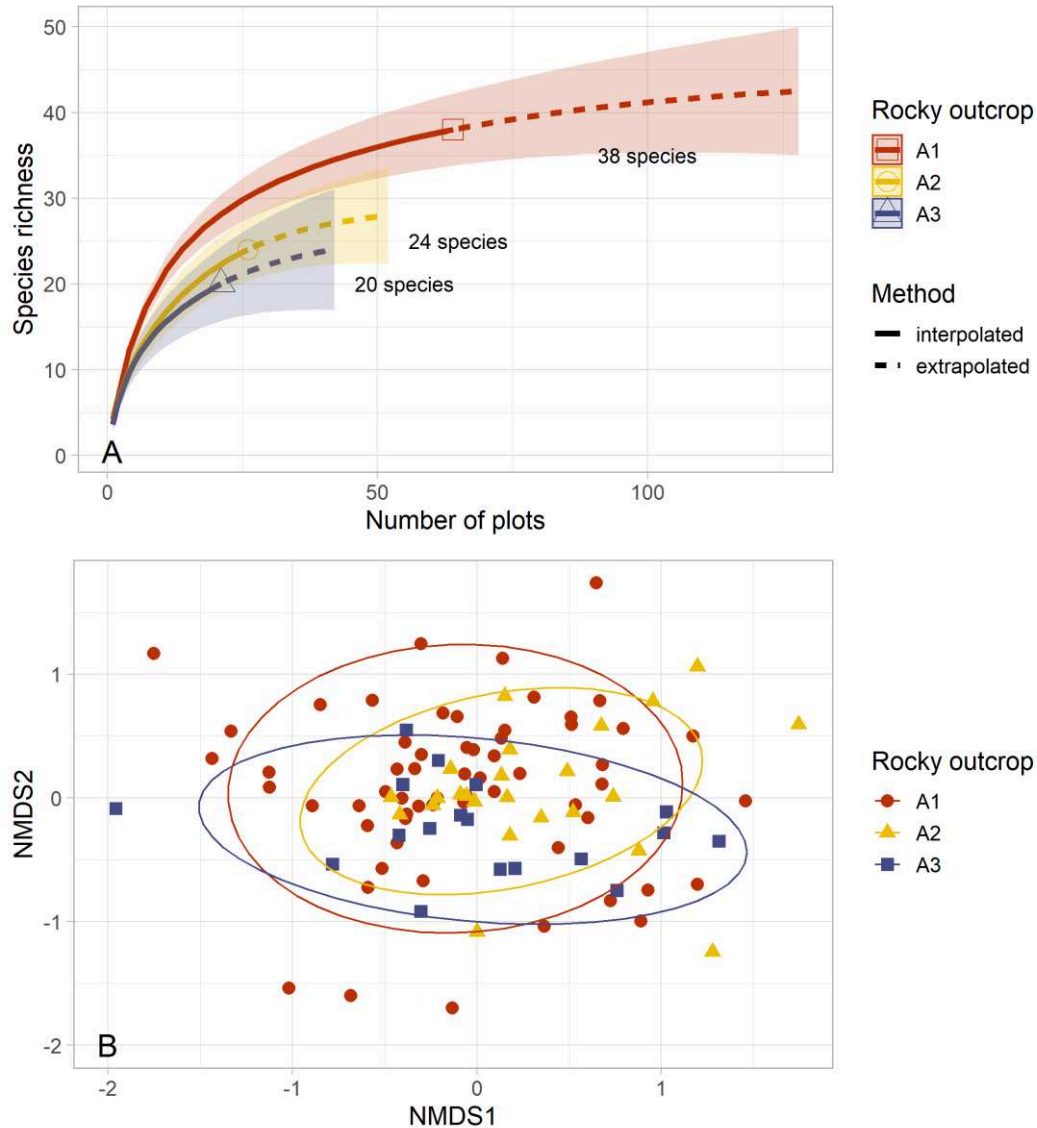


Figure 9. a) Rarefaction and extrapolation curves of plant species diversity based on the first Hill numbers ($q=0$), in three rocky outcrops (A1, A2, and A3) in Harmony Point, Nelson Island; b) Nonmetric multidimensional scaling (NMDS) based on species composition from the three rocky outcrops.

The species richness in bare soil substrate demonstrated a better tendency to establish with the extrapolation, due to its larger number of sampled plots, while the rocky substrate has higher species richness after equalization of sampling effort by the estimated richness (Fig. 10a). The NMDS showed that species composition varied significantly between the two environments (Stress-Euclidean = 0.18; $F_{1,19} = 2.75$; PERMANOVA $p = 0.05$), despite the overlapping (Fig. 10b). The species composition of B environment is present in A, but environment A included a greater number of species not found in B.

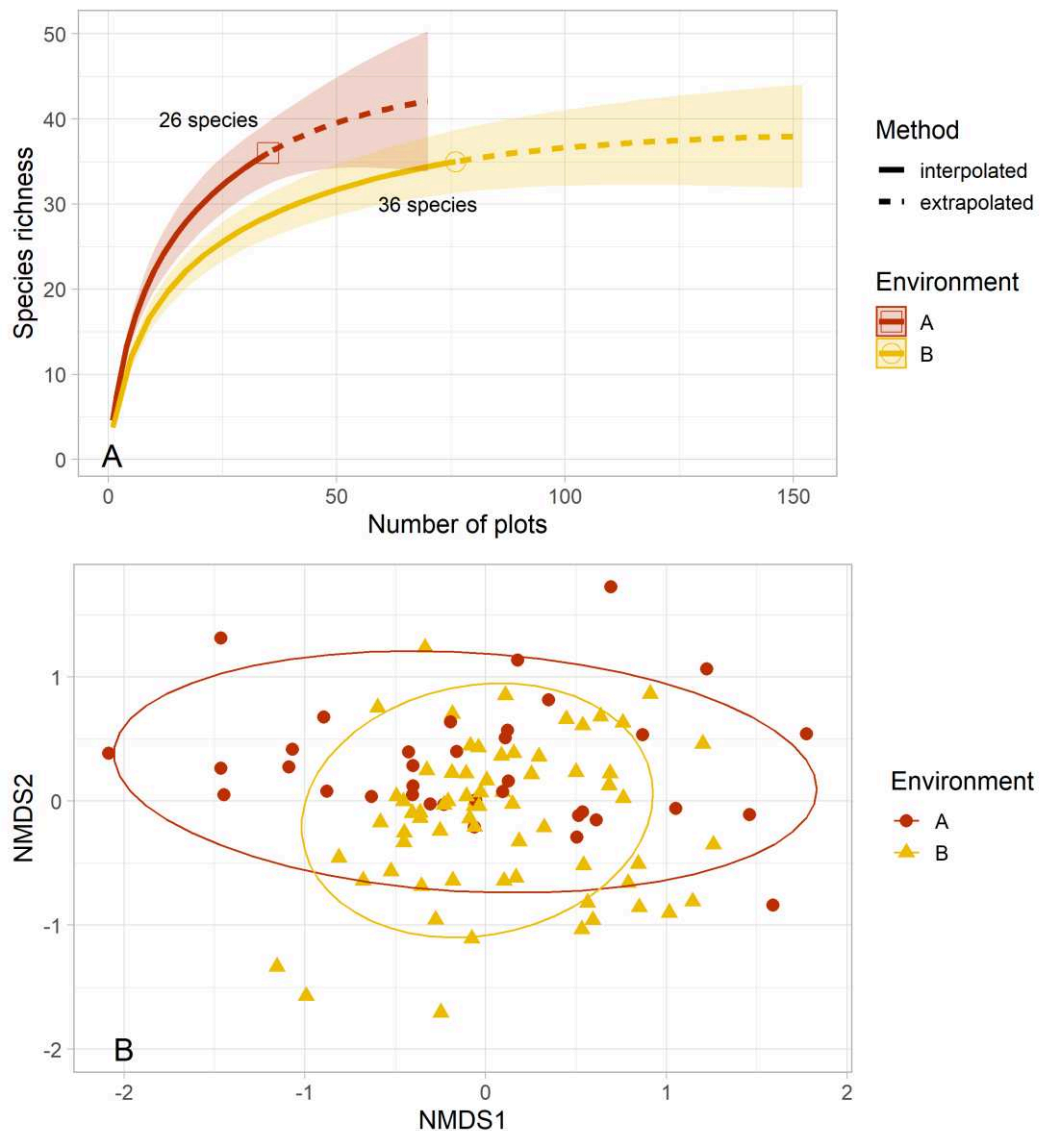


Figure 10. a) Rarefaction and extrapolation curves of plant species diversity based on the first Hill numbers ($q = 0$), in two environments in Harmony Point, Nelson Island, A: rocky substrate; B: bare soil substrate; b) Nonmetric multidimensional scaling (NMDS) based on species composition from the two environments.

3.4 EFFECTS OF POTENTIAL PREDICTORS ON SPECIES RICHNESS

In the multi-model comparison applied including plant species, soil fertility (PCA1f), and soil texture (PCA1t) (Table S2), and the two environments, we found that models including environment groups affect the species richness. Thus, variation in the substrate of the environment negatively affects richness, where growing conditions determine variation in richness (LMM: $t = -2.56$; $p < 0.01$) (Fig. 11). Conversely, soil texture and fertility had no significant influence on species richness (Table S3).

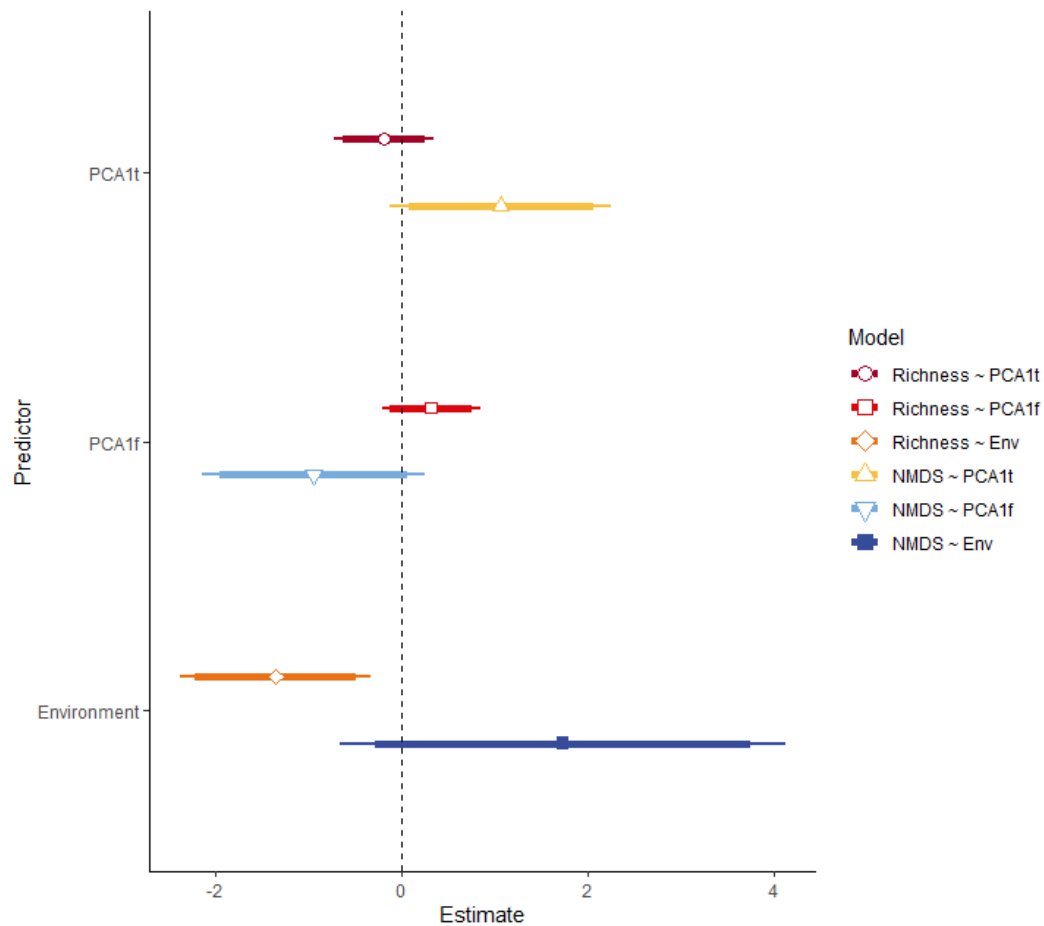


Figure 11. Linear mixed effect models (LMM) explain the main effects of potential predictors on species richness in rocky outcrops in Harmony Point, Nelson Island. NMDS: nonmetric multidimensional scaling as a variability proxy of species composition; PCA1t: principal components of soil texture; PCA1f: principal components of soil fertility; Env: environment A: a rocky substrate; B: bare soil substrate.

4. DISCUSSION

Species richness features prominently in foundational community ecology models and is a key taxonomical metric in conservation biology (Hubbel 2001, Brook et al., 2003; Chao et al., 2014). In this study is possible to confirm, based on the linear mixed effect models, that environmental conditions influence the species richness, and revealed differences between rocky outcrops. Specifically, the habitat-mediated filtering can determine species richness differences in Antarctica vegetation affected by Giant-petrel nests. Our results demonstrated that habitat filtering can be an important driver of plant community further soil-mediated filtering in maritime Antarctica. Most of the studies showed the effects of soil properties (texture and soil fertility) as the main driver along an environmental gradient (Schmitz et al., 2021, 2020a, 2020b), however, few studies have shown how habitat filtering by biological influence may be more important (Putzke et al., 2022).

Descriptive statistical data for the physical contents (Fig. 4) present differences between the outcrops, A3 has coarser sandy than A2 and A1 and inversely amounted to fine sandy particles. Silt and clay demonstrate that the texture of A1 is composed of silt and clay particles, while A2 has less silt, like A3, and more clay particles, less presented in A3. The outcrop's chemical composition distinguishes in some attributes and determines the groups in the PCA and physical properties (Fig. 5). OM and N, properties strongly correlated with ornithogenic influence (Simas et al., 2007; Tatur et al., 1997), grouped the A1 and A2 outcrops, despite A3 presenting the greatest means of OM, probably due to the lowest N values. Both properties exhibited higher correlation with Dim2, and oppositely correlation with Dim1. Even though A3 is not grouped with ornithogenic soil properties, this outcrop had the highest P mean amounts, other properties closely related to ornithogenic influence (Tatur et al., 1997), evidencing the relic influence of the nests. This pattern occurred to K and Na properties. A2 presented the highest K and Na values (520 and 660 mg/dm³, respectively), attributes related to recent penguin activity on King George Island (Simas et al., 2007) with amounts 3 to 4 times higher than the means at A2. Although, Zwolicki et al. (2015) measured differences between seabird colonies (*Pyngoscelis adeliae*, *P. papua*, *Larus dominicanus*, and *Macronectes giganteus*) and found significant composition differences between successive vegetation zones related with clearly distinguished in soil properties along gradients at the colony edges. However, the authors argued that the pattern of vegetation zonation was independent of bird species and colony size. This result highlights the importance of ornithological influence from flying birds. In this study, these properties and Zn, Mg²⁺, and Ca²⁺ are not grouped with any outcrop, despite the correlation between Ca²⁺ and the Dim 1 ($r = 0.76$).

The strong correlation with Mn and Dim 1 ($r = 0.83$) was related to A1 and A2 and with pH values, these factors distinguish these outcrops from A3. Though, these properties are correlated negatively in the axis with OM, N, Al³⁺, and clay properties. Nevertheless, A1 and A2 plots float between these soil properties, showing a large amplitude of the plots and is determined by the negative correlation among them in the axis.

Patterns of species composition were observed between the rocky outcrops, sharing 22 species (Fig. 8). Besides general similarities, there are differences in the patterns between the interpolated species (Fig. 9a), probably due to the differences in the size of the rocky outcrops. A1 is more extensive, sampled with 72 plots and 116 meters (Fig. 6). Larger areas may inflate species richness simply due to the species-area relationship (Baniya et al., 2012).

However, the species richness to concentrated in A2 in NMDS analysis and disperse between A1 and A3 (Fig. 9b).

In addition to the outcrop length difference, the substrate surrounding the outcrops A1 and A3 is different (Fig. 6). In A3 there is a greater established moss carpet in the plots, in contrast to the stone soil of A1, seen also in A2. Lichens tend to predominate in all rocky outcrops and are more representative in environment A, with rock substrate (Table 3). They are more tolerant of the cold and desiccation, and to elevation than phanerogams and mosses (Feuerer and Hawksworth, 2007). On King George Island, Pereira et al. (2007) found crustose lichens typically ornitocoprophilic, such as *Caloplaca* spp. and *Rusavskia elegans* (Link) S.Y. Kondr. & Kärnefelt on a rocky outcrop with *Larus dominicanus* (bird) influence. In the spaces between the rocks a rich community of the miscellaneous type occurs, where *S. uncinata*, and the angiosperms *Deschampsia antarctica* Desv. and *Colobanthus quitensis* (Kunth) are predominant. This pattern was observed in the bare soil substrate, where there is an increase in moss species (Table 3), covering adjacent and at the base of the rocky formation. Changes in the substrate along the outcrops presumably also promote high species turnover between the three rocky fragments, demonstrated by the NMDS (Fig. 10b). Despite overlapping occurring, the species richness is greater distributed in the phytosociology plots. There is also the occurrence of 10 species only in the rocky environment and 12 occurring in exposed soil.

Harmony Point had great-quality soils and lower anthropogenic impact than neighbor islands and was considered a safe baseline for environmental monitoring (Rodrigues et al., 2021). In Antarctica, diverse studies have warned of the potential negative impacts of human activity, increasing regional climate change damage to soil and vegetation (Convey, 2005; Hughes et al., 2020; Robinson et al., 2018; Tin et al., 2009). Convey et al. (2018) related that the ground and sub-surface temperatures for the polar flora and fauna are the patterns of their variation – the microhabitat – that is of greater significance than air temperature per se. Meanwhile, Robinson et al. (2018) highlighted that the Antarctic moss communities are far more responsive to their microclimate based on their slow growth. Therefore, the study of habitat filtering in non-vascular plant communities is important in a terrestrial system where abiotically-driven systems predominated (Hogg et al., 2006)

Outcrops are often used as petrel nests during the summer season for breeding, and their influence is visible in the color pattern of the rocks and changes in the vegetation. In addition to their excrements in the landscape, these birds use regurgitation for defense against predators. Their diet includes both scavenged items (fur seal and penguin carrion) as well as

predated items (krill, squid, small birds) (Hunter, 1983) and provided the input of nutrients (Smith, 1978). Neufeld et al. (2015) related significantly higher N₂O emission at sites influenced by Giant-Petrel due their N contribution, with the largest N₂O accumulated emissions in soils with *P. crispa*. Krüger (2019) related a total of 481 active Giant-petrel nests, distributed in scattered small breeding groups and isolated nests in Harmony Point. The author claimed that these seabird species are decreasing in a few nests in this region, compared to previous studies (Harris et al., 2011). Putzke et al. (2022) demonstrated that nests use or maintenance during breeding Giant-petrel's dynamic can be considered abiotic filter that determines marked changes in community coverage, composition, and species turnover. In this way, changes in the ecosystem and their reflection on the seabird population must be investigated (Krüger, 2019; Putzke et al., 2022). In this study, this environment and its influences are the most predictors of species richness (Fig. 11), acting as a habitat filter, and disturbances in their properties can drive plant species.

These results are important for understanding the ecological drivers of fine-scale variation in population richness and predicting the responses of these communities to environmental changes. Understanding how heterogeneous environments like terrestrial Antarctica and their responses to environmental changes requires studies at multiple spatial and temporal scales (Danis et al., 2020). The fine-scale variation presented in this study regarding community species richness, was best predicted by a model that incorporated both abiotic and biotic influences from the environment, as observed by Potts et al. (2020), and here attributed to soil and flying birds.

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SUPPLEMENTARY MATERIAL:

Table S1: Soil physical and chemistry properties' eigenvalues from axis 1 and 2 (Dim 1 and Dim2) from principal component analysis (PCA).

Soil properties	Axis	
	Dim1	Dim2
Silt	0.48	0.28
Clay	-0.42	0.54
pH H₂O	0.74	-.044
P	0.20	0.23
K⁺	0.65	0.45
Na⁺	0.53	0.37
Ca²⁺	0.76	0.45
Mg²⁺	0.66	0.45
Al³⁺	-0.48	0.69
OM	-0.23	0.84
Cu	0.47	-0.19
Mn	0.83	-0.16
Fe	0.21	-0.44
Zn	0.59	0.57
N	-0.32	0.79

Table S2: Principal components of soil texture (PCA1t and PCA2t) and soil fertility from 121 plots sampled in Harmony Point, Nelson Island.

PCA1t	PCA2t	PCA1f
4.732608105	-1.70648439	-2.249617247
-4.85609198	-1.152372785	-2.110686793
-3.968881917	-1.840144229	-7.472153524
-1.007317044	-1.028040774	-1.041581034
3.330258485	1.584373416	7.348750447
-5.630510515	1.1782017	-6.856431812
-1.547381793	-3.67769621	-1.458631013
3.77616988	2.160066379	-9.152598207
3.160841698	8.628334236	-5.693314167

-5.970366653	6.726989619	-4.349775038
1.330649817	8.498011142	1.937384656
-2.719856709	5.376934671	-7.030532363
3.021742433	-1.830344385	-1.615817669
1.083317209	-2.783842217	-2.195965615
-1.446047374	1.289962037	-7.677243692
6.822104152	9.261213094	-6.729250521
-1.963880316	8.925651457	9.385066752
-2.210154628	-5.686770473	-1.793256607
4.006115572	7.714247455	-1.475813652
-2.65735731	2.194513055	-2.264022187
1.208953071	9.174723249	3.992672226
2.834531255	2.457480754	1.039988519
7.400881344	-1.731726404	-2.455714693
1.179236838	1.227603792	-2.000267592
1.065228969	-1.093797888	-7.172232743
-2.96167378	8.233883988	-1.038055604
-7.698846209	9.711366952	-1.498601314
1.451177781	4.043355796	-5.768678497
1.515625949	3.421120659	-2.399158977
-6.230462996	1.184950151	1.923137288
-7.113153681	-4.169219981	-7.057263209
-6.690992555	-3.956895474	-1.100990831
9.976116409	-7.668473381	-4.852736691
2.070331179	1.253497816	8.863983458
2.311641859	7.254746768	5.309163273
6.200946636	4.682789917	-5.567377855
1.39075811	4.347207565	-2.361766946
3.622897701	1.166992811	2.042806167
4.081436602	2.327118492	-7.085080189
-4.585491184	1.99972556	-1.160080456
-7.113153681	-4.169219981	1.683671999
-1.545765781	-7.517069055	-4.490751343

2.070331179	1.253497816	9.594883298
-8.871664525	-1.272771652	4.361862548
3.622897701	1.166992811	9.996504175
-9.994884772	-3.88368682	1.567223456
2.070331179	1.253497816	2.497835989
2.311641859	7.254746768	4.578443693
6.200946636	4.682789917	2.124107219
-6.576230616	-1.585232833	7.899601363
-6.970212702	-5.110506006	-1.304232236
-7.489321835	1.547428583	2.932817011
-1.821040169	-8.131251684	1.656248568
-3.515204215	-5.698749857	-1.643357785
5.095153282	-1.614139994	-2.335936512
5.88749416	-2.746708384	-3.451450347
-1.930620945	-5.312958919	5.660224949
-1.528207567	4.290960569	-3.557883686
1.08591905	-5.166846764	-1.709419422
9.478135525	-4.043063861	-2.145808109
8.097080555	-2.919280958	1.814561174
6.716025586	-1.795498055	1.31186309
3.14008814	-1.450248433	-1.739261129
1.942258224	-7.232143386	-1.004040333
7.444283075	3.819756065	3.251302151
1.942258224	-7.232143386	-1.004040333
3.14008814	-1.450248433	1.894288234
3.14008814	-1.450248433	-1.739261129
-4.683249244	-1.26575267	1.204605936
-2.537474186	1.223649695	4.183815338
-4.606623448	3.71305206	3.482138896
-1.731016961	-5.013251303	1.575277751
1.846663698	4.069547467	-1.028181882
-1.930620945	-5.312958919	5.660224949
4.532208494	-5.853836794	-9.685135126

1.839591619

8.173844049

-2.284962756

Table S3. Effect models predicting the species richness according to the principal components of soil texture (PCA1t and PCA2t) and soil fertility, and two environments – A: rocky substrate; B: bare soil substrate - from 121 plots sampled in Harmony Point, Nelson Island.

Factors	R ²	Estimate	t.value	p	Standard derivation
PCA1t	0.006	-0.04	-0.654	0.515	2.340
PCA2t	0.014	-0.058	-0.903	0.371	2.338
PCA1f	0.018	0.07	1.059	0.294	2.332
Environment B	0.081	-1.349	-2.569	0.012	2.256
PCA1t	0.04	0.227	1.676	0.098	5.221
PCA2t	0.079	0.243	1.746	0.086	5.165
PCA1f	0.036	-0.207	-1.396	0.168	5.235
Environment B	0.031	1.728	1.414	0.162	5.249

Table S4. Phytosociological data for the rocky outcrop A1, including frequency (F), coverage (C) and index of ecological significance (IES).

Species	F	C	IES
<i>Acarospora macrocyclos</i>	27.14	0.40	38.00
<i>Andreaea gainii</i>	44.29	0.80	79.71
<i>Bryum archangelicum</i>	8.57	0.16	9.92
<i>Buellia anisomera</i>	14.29	0.17	16.73
<i>Bacidia austroshetlandica</i>	11.43	0.13	12.90
<i>Buellia latemarginata</i>	10.00	0.14	11.43
<i>Cladonia borealis</i>	20.00	0.21	24.29
<i>Cystocoleus niger</i>	10.00	0.11	11.14
<i>Conostomum magellanicum</i>	1.43	0.01	1.45
<i>Caloplaca regalis</i>	1.43	0.01	1.45
<i>Haematomma erythromma</i>	18.57	0.27	23.61
<i>Henediella heimii</i>	14.29	0.21	17.35
<i>Himantormia lugubris</i>	5.71	0.07	6.12
Unidentified lichen	22.86	0.34	30.69
<i>Lecania brialmontii</i>	10.00	0.17	11.71
<i>Carbonea assentiens</i>	10.00	0.14	11.43

<i>Mastodea tessellata</i>	1.43	0.04	1.49
<i>Microglæna antarctica</i>	10.00	0.11	11.14
<i>Sanionia uncinata moribund</i>	17.14	0.39	23.76
<i>Ochrolechia antarctica</i>	2.86	0.03	2.94
<i>Ochrolechia frigida</i>	14.29	0.24	17.76
<i>Pannaria hoockeri</i>	1.43	0.01	1.45
<i>Polytrichastrum alpinum</i>	15.71	0.24	19.53
<i>Psoroma cinammomeum</i>	4.29	0.04	4.47
<i>Polytrichastrum alpinum moribund</i>	1.43	0.06	1.51
<i>Prasiola crispa</i>	14.29	0.16	16.53
<i>Pohlia drummondii</i>	1.43	0.01	1.45
<i>Psoroma hypnorum</i>	7.14	0.09	7.76
<i>Polytrichum juniperinum</i>	2.86	0.06	3.02
<i>Physconia muscigena</i>	2.86	0.04	2.98
<i>Rhizocarpon griseolum</i>	2.86	0.03	2.94
<i>Rinodina petermannii</i>	4.29	0.07	4.59
<i>Rhizoplaca aspidophora</i>	1.43	0.03	1.47
Rock	60.00	1.57	154.29
<i>Sanionia georgicouncinata</i>	18.57	0.34	24.94
<i>Sanionia uncinata</i>	54.29	1.66	144.24
Bare soil	5.71	0.19	6.78
<i>Stereocaulon alpinum</i>	2.86	0.03	2.94
<i>Stereocaulon glabrum</i>	1.43	0.03	1.47
<i>Usnea aurantiacoatra</i>	5.71	0.06	6.04
<i>Warnsdorfia sarmentosa</i>	14.29	0.43	20.41

Table S5. Phytosociological data for the rocky outcrop A2, including frequency (F), coverage (C) and index of ecological significance (IES).

Species	F	C	IES
<i>Acarospora macrocyclos</i>	10.71	0.14	12.24
<i>Andreaea gainii</i>	42.86	0.57	67.35
Bare soil	7.14	0.11	7.91
Cyanobacteria	7.14	0.18	8.42

<i>Cystocoleus niger</i>	3.57	0.07	3.83
<i>Cladonia borealis</i>	42.86	0.54	65.82
<i>Chorisodontium aciphyllum</i>	14.29	0.29	18.37
<i>Caloplaca regalis</i>	3.57	0.04	3.70
<i>Henediella heimii</i>	10.71	0.11	11.86
<i>Himatormia lugubris</i>	3.57	0.07	3.83
<i>Lecania brialmontii</i>	3.57	0.04	3.70
<i>Carbonea assentiens</i>	7.14	0.07	7.65
<i>Microglaena antarctica</i>	3.57	0.04	3.70
<i>Sanionia uncinata</i> moribund	32.14	0.43	45.92
<i>Henediella heimii</i> moribund	3.57	0.04	3.70
<i>Ochrolechia frigida</i>	25.00	0.39	34.82
<i>Polytrichastrum alpinum</i>	25.00	0.36	33.93
<i>Polytrichastrum alpinum</i> moribund	3.57	0.07	3.83
<i>Prasiola crispa</i>	3.57	0.04	3.70
<i>Polytrichum juniperinum</i>	3.57	0.04	3.70
<i>Psoroma hypnorum</i>	7.14	0.07	7.65
<i>Rhizocarpon griseolum</i>	10.71	0.11	11.86
Rock	60.71	1.64	160.46
<i>Sanionia georgicouncinata</i>	7.14	0.21	8.67
<i>Sanionia uncinata</i>	71.43	2.54	252.55
Snow cover	3.57	0.18	4.21
<i>Stereocaulon alpinum</i>	7.14	0.18	8.42
<i>Syntrichia princeps</i>	3.57	0.04	3.70
Unidentified lichen	28.57	0.39	39.80
<i>Usnea aurantiaco-atra</i>	7.14	0.07	7.65

Table S6. Phytosociological data for the rocky outcrop A3, including frequency (F), coverage (C) and index of ecological significance (IES).

Species	F	C	IES
<i>Acarospora macrocyclos</i>	23.81	0.33	31.75
<i>Andreaea gainii</i>	4.76	0.05	4.99
<i>Andreaea regularis</i>	28.57	0.29	36.73

<i>Bacidia austroshetlandica</i>	4.76	0.05	4.99
<i>Carbonea assentiens</i>	4.76	0.10	5.22
<i>Catillaria corymbosa</i>	4.76	0.05	4.99
<i>Cladonia borealis</i>	19.05	0.19	22.68
<i>Cystocoleus niger</i>	19.05	0.19	22.68
<i>Himatormia lugubris</i>	9.52	0.10	10.43
<i>Ochrolechia antarctica</i>	9.52	0.10	10.43
<i>Ochrolechia frigida</i>	33.33	0.57	52.38
<i>Prasiola crispa</i>	9.52	0.14	10.88
<i>Pohlia drummondii</i>	4.76	0.10	5.22
<i>Psoroma hypnorum</i>	19.05	0.24	23.58
<i>Rhizocarpon griseolum</i>	9.52	0.14	10.88
Rock	42.86	0.52	65.31
<i>Sanionia georgicouncinata</i>	57.14	2.00	171.43
<i>Sanionia uncinata</i>	61.90	2.52	218.14
Undertified lichen	28.57	0.48	42.18
<i>Usnea aurantiaco-atra</i>	4.76	0.05	4.99
<i>Warnsdorfia sarmentosa</i>	4.76	0.24	5.90

CAPÍTULO IV:

**Classification of ice-free areas: machine learning algorithms combined with the study of
vegetation in areas of glacial retreat**

ABSTRACT

FERRARI, Flávia, D.Sc., Universidade Federal de Viçosa, May, 2022 **Classification of ice-free areas: machine learning algorithms combined with the study of vegetation in areas of glacial retreat.** Adviser: Carlos Ernesto Gonçalves Reynaud Schaefer. Co-adviser: Marcio Rocha Francelino and Jair Putzke.

Mapping the Antarctic ice-free areas on a large scale can result in gains in ecosystems that need high field research efforts. Monitoring the vegetation distribution and the glacier retreat are key factors that predict environments responses due to the climate change. In this study, we aimed to (1) map the ice-free areas of Demay Point, King George Island, (2) predict the main performance of machine learning algorithms in mapping the vegetation cover, and (3) measure the glacier retreat. We identified 11 plant communities in the field and produced an orthomosaic with high resolution from drone aerial images. Maps of manual classification and machine learning using the models avNNet, kkn and rf were predicted, based in 10 classes. The glacier retreat was compared with aerial photos from 1956, 2007 and the orthomosaic from 2020. The avNNet algorithm proved to be superior to others in predicting the vegetation, bare soil, and glaciers in the Antarctic region with 0.56 of accuracy. When comparing the automatic and manual mapping, differences occurred in diverse situations, but machine learning is useful in predicting ice-free areas and may help the field efforts. Under the current climate change scenario, this study acquires high relevance as it suggests that the ice-free areas increased 5 km² in 64 years, and identified the vegetated sites, providing a large dataset for future monitoring of vegetation colonization in these ice-free portions of King George Island.

Keywords: Antarctic vegetation. Vegetation mapping. Prediction.

1. INTRODUCTION:

The Antarctic terrestrial ecosystems are expected to show particular sensitivity to the processes of environmental change (Convey, 2005), and limited resistance to even small fluctuations (Smith, 1990; Robinson et al., 2003). Composed almost entirely of cryptogams, the vegetation in the Antarctic environment is determined by low summer temperature, water availability, and exposure, controlling the distribution, growth, and form types (Longton, 1979) and driving diversity (Chown et al., 2015). To identify overall vegetation changes in range, good baseline knowledge of distributional limits is essential (Convey et al., 2011), as an understanding of how diversity patterns and the mechanisms underlying them vary among major groups and areas (Chown et al., 2015).

Very accurate and high-quality digital elevation models (DEMs) and orthomosaics have become increasingly used in the Earth sciences, allowing for centimetric to decimetric resolutions even over large areas (Cihlar, 2000). For this purpose, a variety of classification methods have been developed (Rodriguez-Galiano et al., 2012). When one knows what classes are desired and where they occur (at least as a sample), supervised classification strategies are preferable. Thus, where spatial distribution information is not available, e.g., when mapping a large area previously not well known, unsupervised classification is arguably the better strategy (Cihlar, 2000). Although, various alternative machine learning algorithms can be used to perform map classifications, such as Weighted k-Nearest Neighbors (kkn) (Schliep et al., 2016), that are widely accepted, with greater precision and better performance (Siqueira et al., 2022), the Artificial Neural Networks (avNNet) (Ripley, 1996) and the Random Forest (rf) (Breiman, 2001).

Despite being used to classify several tropical environments (e.g. Gomes et al., 2019; Silveira et al., 2022), studies have been demonstrated that aerial and satellite imagery may be used for Antarctic vegetation monitoring, showing a close association between normalized difference vegetation index (NDVI) classes and Antarctic vegetation type (e.g., Casanovas et al., 2015; Jawak et al., 2019; Sotille et al., 2020), and used to classify antarctic landforms (e.g., Siqueira et al., 2022). Fretwell et al. (2011) classified 44.6 km² of the Antarctic Peninsula with a probability of vegetation over 50% utilizing remote sensing. Despite that, the studies focused on detecting the vegetation presence or absence and the utilization of digital image data that can provide long-term information from remote areas.

The reconstruction of the past glacial retreat allows the understanding of the stages of landscape formation and the possible proposition of comparative models between

evolutionary scenarios of these environments. Thus, there is a lack of studies that relate the process of glacier retraction to the plant colonization of these newly exposed areas, from which it will be possible to identify vegetation patterns and their interconnections with glacial dynamics. It is known that investigations of potential impacts on biodiversity require knowledge of the richness and actual distributions of organisms in polar regions (Barners and Kaiser, 2007). Carrying out floristic mapping and comparing the biodiversity of the recent past with the current one through the use of modern techniques can shed light on the percentage of erosion, invasion, and evolution of new species and communities in the polar regions (Singh et al., 2010). The retraction and expansion of ice sheets have been reported as a characteristic phenomenon, with the retreat of the ice, the exposed surface is subject to the action of a new set of factors, as fluvial, slope, and wind systems operate towards the rebalancing of the then non-glacial environment (Benn & Evans, 2010; Anderson et al., 2013; Machado et al., 2019). Several studies reported glacier retreat along the Antarctic Peninsula (e.g., Cook et al., 2016, 2005), and on the South Shetland Island (e.g., Calvet et al., 1999; Simões et al., 1999).

In this context, this study had three main goals. First, we aimed to contribute to the improvement of the current vegetation map of the Demay Point, maritime Antarctica. Secondly, to predict the main performance of machine learning algorithms in the mapping of Antarctic vegetation. Third, to measure glacier retreat and consequently ice-free areas over the years.

2. MATERIALS AND METHODS

2.1 STUDY AREA

Demay Point is an Antarctic Specially Protected Area n° 128 (ASPA 128) (Final Report of the Thirty-Seventh Antarctic Treaty Consultative Meeting, 2014) due to its biodiversity richness in antarctic birds, marine mammals, and vegetation. Covering about 17km² in King George Island (Fig. 1c), the largest island of South Shetlands (Fig. 1b), and provides a representative sample of the maritime Antarctic ecosystem. The island is separated from the Antarctic Peninsula by the Bransfield Strait distance of 120-130 km.

Pereira et al. (2010) describe the vegetation based on classification and description of the plant communities based mainly on the plant physiognomy, biodiversity, and the relation with local abiotic factors. They found seven plant communities where Fellfield communities

predominated with 81.73% cover with deposition of rock fragments or coarse non-consolidated sediments.

The annual mean temperature and the relative air humidity during 2013-2017, in Arctowski Station, near the study area, were -1.7°C and 78.1%, respectively, and the mean annual precipitation in 2017 was 499.8 mm (Plenzler et al., 2019). The area was visited in February 2020.

This region is influenced by glacier fronts of the Sphinx Glacier, Baranowski Glacier, and Windy Glacier located in the southern, that in this study is considered divided into Tower Glacier and Thawing Glacier to measurement (Pasik et al., 2021). These glaciers are part of the Warszawa Icefield along with Ecology Glacier. Baranowski Glacier is the most southern fragment of Warszawa Icefield carrying ice masses directly to Admiralty Bay (Rachlewicz, 1999). In addition to Demay Point, this study covered the regions denominated Agata Point, north of Demay and accessed only by drone due to the large flow of the melt channel and high tide, and Telefon Point, in western in the same portion of the KGI.

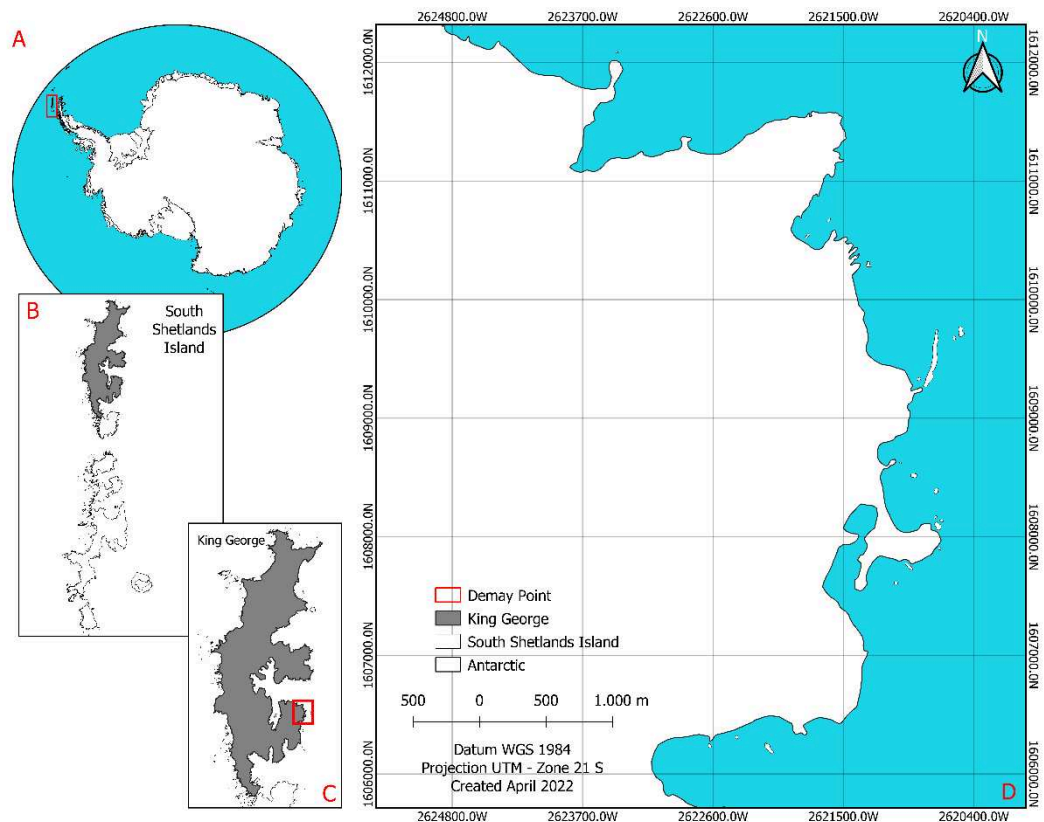


Fig. 1: Localization of the study area in relation to Antarctica (A). The South Shetlands Islands (B), the King George Island (C), and the terrestrial ecosystems studied (D).

2.2 FIELD VEGETATION MAPPING

We identified 11 plant communities through square phytosociological surveys. The samples had 20 x 20 cm (Schmitz et al., 2018) to record the frequency and coverage degree of each species identified. The sites were selected based on the distribution of communities and representing the different compositions between the total area possible to access. These areas will serve as a basis for the construction and training of not supervised mapping classes. The total samples were established in 15 squares per area tracing lines with 5-meter spacing.

The classification of plant communities was determined by the index of ecological significance (IES), which combines parameters of abundance (coverage and frequency) and which plant communities and associations were classified (Lara and Mazimpaka, 1998), through the formulas:

$$IES = F(1+C) \quad (1)$$

where F is the relative frequency of the species in each area (Gimingham and Smith, 1970), and C is the mean species cover in the samples:

$$F = 100x/n \quad (2)$$

$$C = \sum(c_i)/x \quad (3)$$

x is the number of occurrences, n is the number of samples considered, and c_i is the cover class.

To identify plant species we used specific literature, such as Putzke and Pereira (2001) and Ochyra et al. (2008) for mosses, and Ovstedal and Smith (2001) and Olech (2004) for lichens, when possibly.

2.3 SPATIAL DISTRIBUTION OF VEGETATION

For the acquisition of the aerial images, we utilized the Phantom 4 Pro, though 23 of the 31 autonomous flights programmed in the drone mapping software DroneDeploy, taking 2452 aerial photographs in approximately 12-15 min of flight time due to the weather antarctic characteristics. Flights were carried out in periods when weather conditions were most suitable for the better distinguishing of land and ice cover.

All images were processed to the orthomosaic, created the dense point cloud and the digital elevation model (DEM) with 0.05-m resolution using Agisoft Photoscan software. Processing workflow and parameters were set according to official Agisoft guidelines (Agisoft, 2018). The coordinate reference system for the data was WGS84 21S. The orthomosaic was converted to the UTM system, zone 21S (EPSG:32721), with and resolution

of 0.15 cm. This allowed us to generate maps of vegetation distribution using the QGIS software.

2.4 PREDICTORS

We considered 10 classes for the automatic classification. To differentiate the ice cover and to measure the glacier length, we created the (1) glacier and the (2) snow cover classes. The (3) lakes were classified to measure the channels melting available during the antarctic summer. The vegetation cover was distinguished in (4) phanerogamic, (5) macroalgae, (6) moss carpet, (7) mixed composition, (8) fruticose lichen, and (9) crustose lichen classes, according to the phytosociological survey. The (10) exposed soil class was obtained using the Arcgis “Erase” tool, creating a feature class by overlapping the Input Features with the polygons of the Erase Features. Only those portions of the input feature falling outside the erase features outside boundaries are copied to the output feature class.

2.5 MODELING CLASSIFICATION

In the orthomosaic with 0.15 cm resolution, we collected 80 balanced samples with 4 x 4 pixels length in each class previously determined, where the samples represented the range of different colors and spatial distributions corresponding to the same class. The total areas were measured in square kilometers (km²) through the sum of all polygons of each class. The polygons were transformed into raster to compare between all models. The modeling was done by machine learning techniques and classification algorithms. The methodological framework is defined in figure 2.

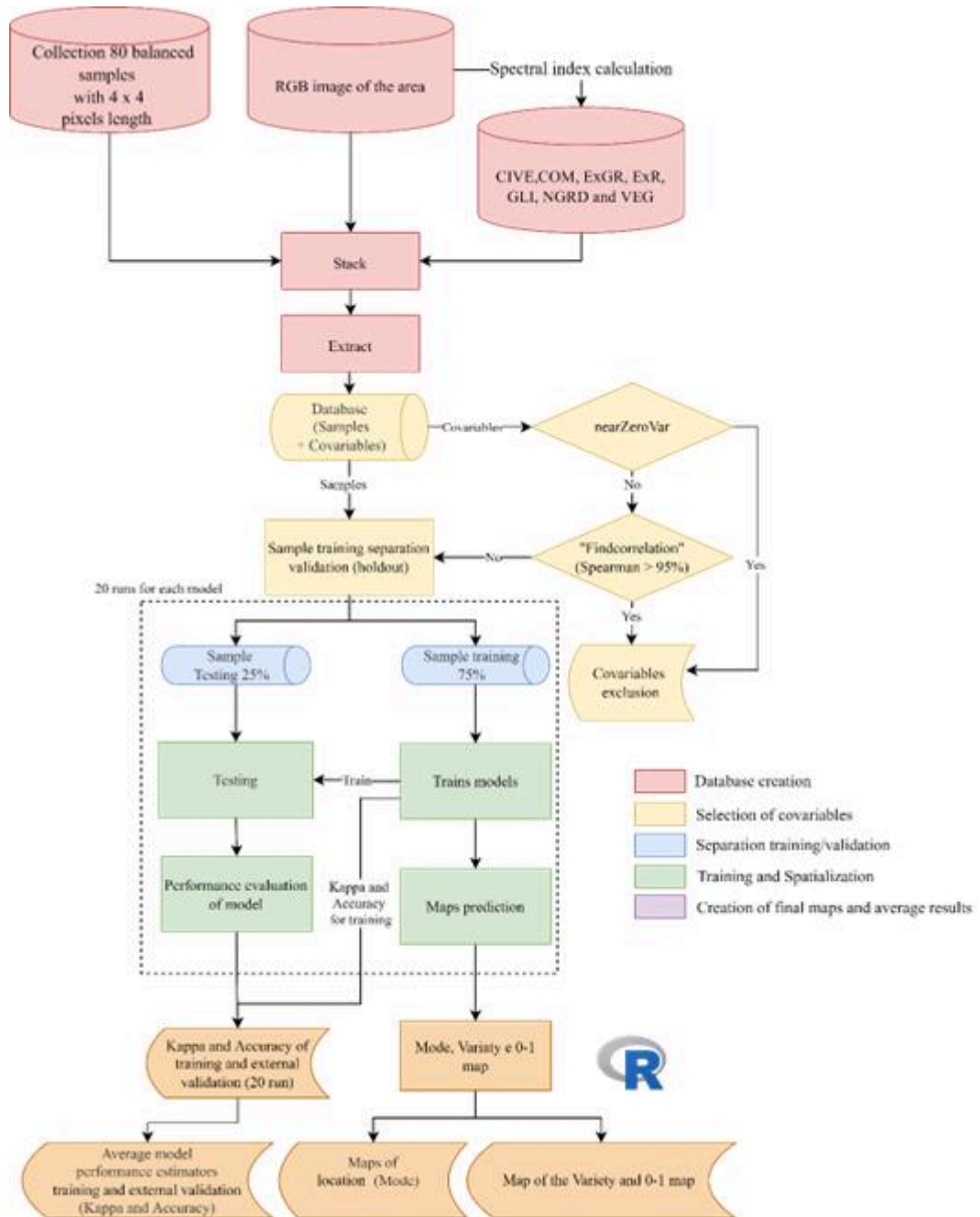


Figure 2. Methodological flowchart used in modeling by machine learning to map/predict ice-free areas of Demay Point.

2.6 ALGORITHMS

We tested three algorithms used to model the map: the *Artificial Neural Networks* - avNNNet (Ripley 1996), *Random Forest* – RF (Breiman 2001), and *k-Nearest Neighbors* – kkn (Schliep et al., 2016).

2.7 TRAINING AND VALIDATION

The performance of the algorithms was measured through accuracy and kappa. The overall accuracy represents the total correct hits related to the total number of pixels. While Kappa coefficient is a statistical technique for the evaluation of agreement or disagreement in two situations of interest, varying from 0 to 1 (Congalton, 1991). The precision of presence-absence predictions was measured using sensitivity and specificity.

For each model, the process was repeated 20 times with its on subset of variables and compared by the mean values of the precision variables.

2.7 GLACIER FRONT DISTANCE

The length of glacier retreats were measured by comparing two images of the region with the orthomosaic created in the present study.

- ARX26FID003907011 image, acquired by British Antarctic Survey on December 20, 1956, and georeferenced to WGS 84 / UTM Zone 21S. Center latitude 62°11'57.69''S, center longitude 58°28'41.59''W, with a spatial resolution of 90 cm. (USGS Earth Explorer).

- Quick Bird satellite image from January 2007, with a spatial resolution of 61 cm.

The glacier retreat area was obtained through polygons covering the entire area of exposed soil in each image. The orthomosaic was converted to 60 cm resolution and plotted the polygons for comparison purposes.

3. RESULTS

The orthomosaic georeferenced was generated to provide relative quality control to map all vegetation cover and proved to be a higher quality product to distinguish the very small vegetation patches and to delineate melting lines and glacier contours (Fig. 3). This study investigates the ability of algorithms classification to identify Antarctic vegetation cover coupled with field sampling efforts.

3.1 PLANT COMMUNITIES

Based on 11 plant communities described through 165 plots, we identify five plant formations and seven distinct associations (Table 1). The classification of communities and associations was according to the species with the highest IES from 50, values that reveal significant ecological importance (Lara and Mazimpaka, 1998). Phanergamic communities predominated in the sample areas, with six communities forming association mainly between the grass *Deschampsia antarctica* Desv. and distinct moss species (Fig. 3). We identified 32

samples to species level, and seven species and the cyanobacteria were not possible to identify.

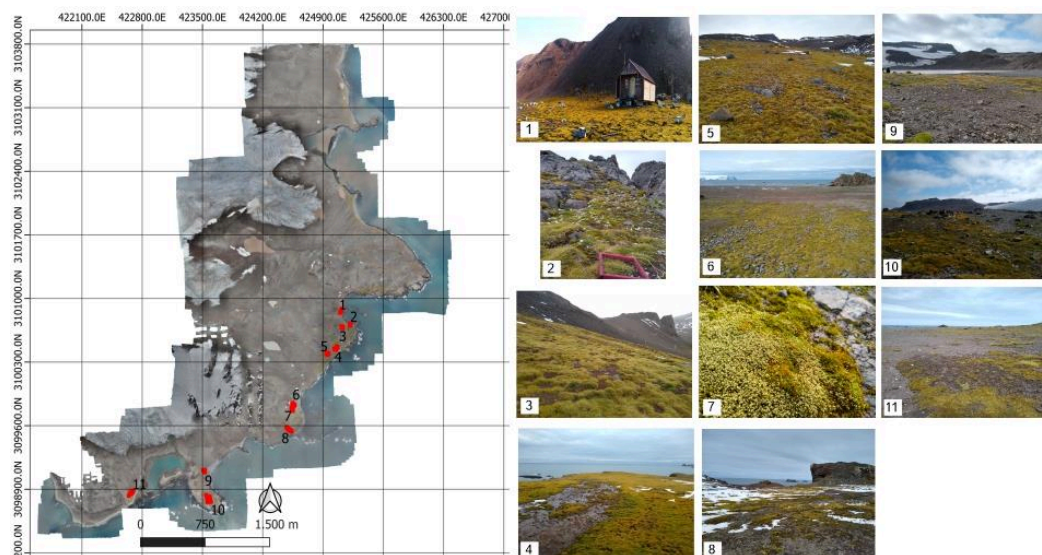


Fig. 3: Demay Point region - King George Island and its 11 plant communities sampled during the baseline survey for classification models. 1: Phanerogamic Community – *Deschampsia* – *Syntrichia* association; 2: Phanerogamic Community – *Deschampsia* – *Prasiola* association; 3: Phanerogamic Community – *Deschampsia* – *Prasiola* association; 4: Moss carpet Community – *Sanionia* – *Warnstorfia* association; 5: Mixed Community – *Deschampsia* – *Polytrichastrum* association; 6: Phanerogamic Community – *Deschampsia* – *Colobanthus* association; 7: Moss cushion Community - *Bryum* – *Deschampsia* association; 8: Moss carpet community – *Sanionia* – *Bryum* association; 9: Phanerogamic Community – *Deschampsia* – *Colobanthus* association; 10: Macroalgae community – *Prasiola* – *Deschampsia* association; 11: Phanerogamic Community – *Deschampsia* – *Bryum* association.

Table 1: Plant communities and their association from Demay Point, King George Island, maritime Antarctica classified according to the higher index of ecological significance.

Species	Frequency (%)	Coverage (%)	Index of ecological significance
01 – Phanerogamic Community – <i>Deschampsia</i> – <i>Syntrichia</i> association			
<i>Deschampsia antarctica</i> Desv.	85.7	3.43	380
<i>Syntrichia magellanica</i> (Mont.) RH Zander	42.9	0.79	76.5
<i>Colobanthus quitensis</i> (Kunth) Bartl.	35.7	0.43	51
<i>Bryum</i> sp	21.4	0.21	26
<i>Acarospora macrocyclos</i> Vain.	14.3	0.14	16.3
<i>Lecanora skottsbergii</i> Darb.	14.3	0.14	16.3
<i>Deschampsia antarctica</i> moribund	7.14	0.14	8.16
<i>Prasiola crispa</i> (Lightfoot) Menegh.	7.14	0.07	7.65
<i>Sanionia uncinata</i>	7.14	0.07	7.65
<i>Usnea antarctica</i> Du Rietz	7.14	0.07	7.65
Undetified lichen 1	7.14	0.07	7.65
Undetified lichen 2	7.14	0.07	7.65
02 – Phanerogamic Community – <i>Deschampsia</i> – <i>Prasiola</i> association			
<i>Deschampsia antarctica</i> moribund	160	1.6	416
<i>Deschampsia antarctica</i>	153	1.53	388

<i>Prasiola crispa</i>	113	1.13	242
<i>Lecanora skottsbergii</i>	66.7	0.67	111
<i>Syntrichia magellanica</i>	53.3	0.53	81.8
<i>Colobanthus quitensis</i>	26.7	0.27	33.8
<i>Lecania brialmontii</i> (Vain.) Zahlbr.	13.3	0.13	15.1
<i>Syntrichia magellanica</i> moribund	6.67	0.07	7.11
Undertified lichen 2	6.67	0.07	7.11
<i>Ochrolechia antarctica</i> (Müll.Arg.) Darb.	6.67	0.07	7.11
Undertified lichen 1	6.67	0.07	7.11
<i>Parmelia saxatilis</i> (L.) Ach.	6.67	0.07	7.11
<i>Gondwania sublobulata</i> (Nyl.) S.Y. Kondr., Kärnefelt, Elix, A. Thell, J. Kim, M.-H. Jeong, N.-N. Yu, A.S. Kondratiuk & J.-S	6.67	0.07	7.11
<i>Leptogium puberulum</i> Hue	6.67	0.07	7.11
03 – Phanerogamic Community – <i>Deschampsia</i> – <i>Prasiola</i> association			
<i>Deschampsia antarctica</i>	80	2.73	299
<i>Prasiola crispa</i>	40	0.4	56
<i>Syntrichia magellanica</i>	33.3	0.4	46.7
<i>Colobanthus quitensis</i>	33.3	0.33	44.4
<i>Sanionia uncinata</i> Loeske	26.7	0.53	40.9
<i>Lecanora skottsbergii</i>	20	0.27	25.3
<i>Bryum</i> sp	13.3	0.13	15.1
<i>Deschampsia antarctica</i> moribund	6.67	0.13	7.56
Undertified lichen 3	6.67	0.07	7.11
<i>Cladonia sublobulata</i> (L.) Weber ex F. H. Wigg.	6.67	0.07	7.11
<i>Usnea antarctica</i>	6.67	0.07	7.11
04 – Moss carpet Community – <i>Sanionia</i> – <i>Warnstorffia</i> association			
<i>Sanionia uncinata</i>	53.33	4.27	280.88
<i>Sanionia uncinata</i> moribund	60.00	0.67	100
<i>Warnstorffia sarmentosa</i> (Wahlenb.) Hedenäs	13.33	0.20	16
<i>Polytrichastrum alpinum</i> Hedw.	13.33	0.07	14.22
<i>Deschampsia antarctica</i>	6.67	1.07	13.77
<i>Syntrichia saxicola</i> Zander	6.67	0.20	8
<i>Bryum orbiculatifolium</i> Cardot & Broth.	6.67	0.20	8
<i>Colobanthus quitensis</i>	6.67	0.13	7.55
<i>Psoroma cinnamomeum</i> Malme	6.67	0.07	7.11
<i>Leptogium puberulum</i>	6.67	0.07	7.11
05 – Mixed Community – <i>Deschampsia</i> – <i>Polytrichastrum</i> association			
<i>Deschampsia antarctica</i>	86.67	2.13	271.56
<i>Polytrichastrum alpinum</i>	86.67	1.47	213.78
<i>Psoroma hypnorum</i> (Vahl) Grey	66.67	1.20	146.67
<i>Colobanthus quitensis</i>	66.67	1.07	137.78
<i>Ochrolechia frigida</i> (Sw.) Lynge	60.00	0.60	96.00
<i>Sanionia uncinata</i>	40.00	0.80	72.00
<i>Colobanthus quitensis</i> moribund	40.00	0.53	61.33
<i>Lecanora skottsbergii</i>	20.00	0.33	26.67
<i>Usnea antarctica</i>	20.00	0.27	25.33
<i>Sanionia georgicouncinata</i> Ochyra	13.33	0.53	20.44
<i>Polytrichum juniperinum</i> Hedwig	6.67	0.07	7.11

<i>Psoroma cinnamomeum</i>	6.67	0.07	7.11
<i>Caloplaca regalis</i> (Vain.) Zahlbr.	6.67	0.07	7.11
06 – Phanerogamic Community – <i>Deschampsia</i> – <i>Colobanthus</i> association			
<i>Deschampsia antarctica</i>	80.00	2.93	314.67
<i>Colobanthus quitensis</i>	66.67	0.73	115.56
<i>Acarospora macrocyclos</i>	40.00	0.40	56.00
<i>Prasiola crispa</i> moribund	33.33	0.33	44.44
<i>Deschampsia antarctica</i> moribund	20.00	0.20	24.00
<i>Prasiola crispa</i>	20.00	0.20	24.00
<i>Sanionia uncinata</i>	13.33	0.60	21.33
<i>Rhizoplaca aspidophora</i> (Vain.) Redón	13.33	0.13	15.11
<i>Buellia latemarginata</i> Darb.	13.33	0.13	15.11
<i>Gondwania subobulata</i>	13.33	0.13	15.11
<i>Colobanthus quitensis</i> moribund	6.67	0.07	7.11
<i>Parmelia saxatilis</i>	6.67	0.07	7.11
<i>Lecania brialmontii</i>	6.67	0.07	7.11
<i>Lecanora skottsbergii</i>	6.67	0.07	7.11
<i>Bryum</i> sp.	6.67	0.07	7.11
07 - Moss cushion Community - <i>Bryum</i> – <i>Deschampsia</i> association			
<i>Bryum</i> sp.	73.33	1.40	176
Unidentified cyanobacteria	46.67	0.93	90.2
<i>Deschampsia antarctica</i>	53.33	0.67	88.9
<i>Sanionia uncinata</i>	26.67	0.47	39.1
<i>Acarospora macrocyclos</i>	13.33	0.13	15.1
<i>Bryum orbiculatifolium</i>	6.67	0.13	7.56
<i>Bryum</i> sp. moribund	6.67	0.07	7.11
<i>Leptogium puberulum</i>	6.67	0.07	7.11
<i>Colobanthus quitensis</i>	6.67	0.07	7.11
<i>Syntrichia filaris</i> Zander	6.67	0.07	7.11
Unidentified lichen 4	6.67	0.07	7.11
08 – Moss carpet community – <i>Sanionia</i> – <i>Bryum</i> association			
<i>Sanionia uncinata</i>	83.33	2.93	328
<i>Sanionia uncinata</i> moribund	66.67	1.43	162
<i>Bryum</i> sp	26.67	0.43	38.2
Bare soil	23.33	0.60	37.3
<i>Deschampsia antarctica</i>	26.67	0.33	35.6
<i>Ochrolechia frigida</i>	13.33	0.17	15.6
<i>Polytrichastrum alpinum</i>	13.33	0.13	15.1
<i>Acarospora macrocyclos</i>	13.33	0.13	15.1
<i>Psoroma hypnorum</i>	10.00	0.10	11
Unidentified cyanobacteria	6.67	0.20	8
<i>Cladonia</i> sp	6.67	0.13	7.56
<i>Bryum pseudotriquetrum</i> (Hedw.) P. Gaertn., B. Mey. & Scherb.	6.67	0.07	7.11
<i>Lecanora skottsbergii</i>	6.67	0.07	7.11
<i>Colobanthus quitensis</i>	3.33	0.03	3.44
09 – Phanerogamic Community – <i>Deschampsia</i> – <i>Colobanthus</i> association			
<i>Deschampsia antarctica</i>	86.67	2.40	294.67
Rock	93.33	1.67	248.89
Bare soil	73.33	2.20	234.67

<i>Colobanthus quitensis</i>	80.00	1.00	160.00
<i>Prasiola crispa</i>	46.67	0.93	90.22
<i>Deschampsia antarctica</i> moribund	20.00	0.27	25.33
<i>Caloplaca cinericola</i> (Hue) Darb	20.00	0.20	24.00
<i>Prasiola crispa</i> moribund	13.33	0.13	15.11
Undidentified lichen 3	13.33	0.13	15.11
<i>Caloplaca regalis</i>	6.67	0.07	7.11
<i>Colobanthus quitensis</i> moribund	6.67	0.07	7.11
<i>Gondwania subobulata</i>	6.67	0.07	7.11
10 – Macroalgae community – <i>Prasiola</i> – <i>Deschampsia</i> association			
<i>Prasiola crispa</i> moribund	80.00	2.1	248
<i>Deschampsia antarctica</i>	63.33	1.8	177
<i>Prasiola crispa</i>	56.67	0.7	96.3
<i>Colobanthus quitensis</i>	20.00	0.2	24
<i>Mastodia tessellata</i> Hook. f. & Harvey	6.67	0.10	7.33
<i>Acarospora macrocyclos</i>	6.67	0.07	7.11
<i>Deschampsia antarctica</i> moribund	3.33	0.1	3.67
<i>Lecanora skottsbergii</i>	3.33	0.07	3.56
Unidentified cyanobacteria	3.33	0.03	3.44
<i>Lecania brialmontii</i>	3.33	0.03	3.44
<i>Verrucaria</i> sp	3.33	0.03	3.44
11 - Phanerogamic Community – <i>Deschampsia</i> – <i>Bryum</i> association			
<i>Deschampsia antarctica</i>	65.38	1.85	186.09
<i>Bryum</i> sp	61.54	1.73	168.04
<i>Prasiola crispa</i> moribund	19.23	0.27	24.40
<i>Prasiola crispa</i>	15.38	0.15	17.75
<i>Prasiola crispa</i> moribund	3.85	0.12	4.28
<i>Deschampsia antarctica</i> moribund	3.85	0.04	3.99
<i>Rusavskia elegans</i> (Link) S.Y. Kondr. & Kärnefelt	3.85	0.04	3.99

3.2 MAPPING VEGETATION COVER

The visual interpretation resulted in a manual classification (Fig. 4) starting with the delineation of plant communities from the phytosociology points marked in the field. To identify these communities, we plot the points in the georeferenced orthomosaic and determined the limit of communities reaching according to the patches of vegetation in the image of the same pixel coloration. The map is the result of sampling 10550 polygons, merging features of the same polygon using the "merge" tool.

Fruticose lichens covered a large part of the portion denominated Demay Point, with a sparse distribution and dark coloration that was difficult to identify.

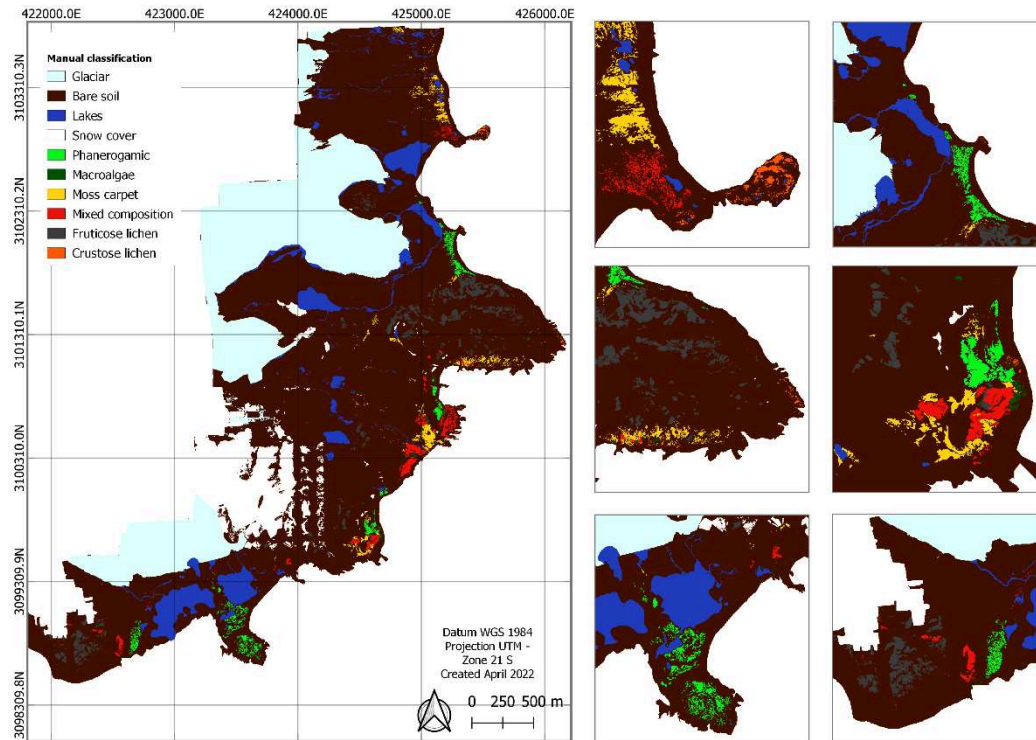


Fig. 4: Manual classification of Demay Point, King George Island, maritime Antarctica, according to 10 classes.

The analyzed algorithms presented accuracy values ranging from 0.58 to 0.66, and kappa from 0.55 to 0.61 in the training of the classification. In general, kkn and RF presented the same values of accuracy (0.63) and similarly in kappa (0.61 and 0.60, respectively). The mean accuracy value of validation was inversely of training, and avNNet presented the best performance, with 0.56 of accuracy and 0.53 of kappa (Fig. 5). In addition, the avNNet presented the lowest overfitting values, close to zero, suggesting that the training and prediction samples were sufficient to enable mapping (Table 2). The three models produced the same specificities values and higher than 80%, corresponding high capacity to avoid false negatives, but all sensitivities presented lower than 80% values but still higher than 50%, which avoids false positives. The models kkn and RF presented the same higher values of specificities than avNNet.

The errors occur when other classes are identified by the classifiers as the class of interest (vegetation). This is evident when comparing the three models with the manual map (Fig. 4, 6-8). Despite that, the avNNet model showed the better distribution of classes, with more homogeneous patterns than kkn and rf.

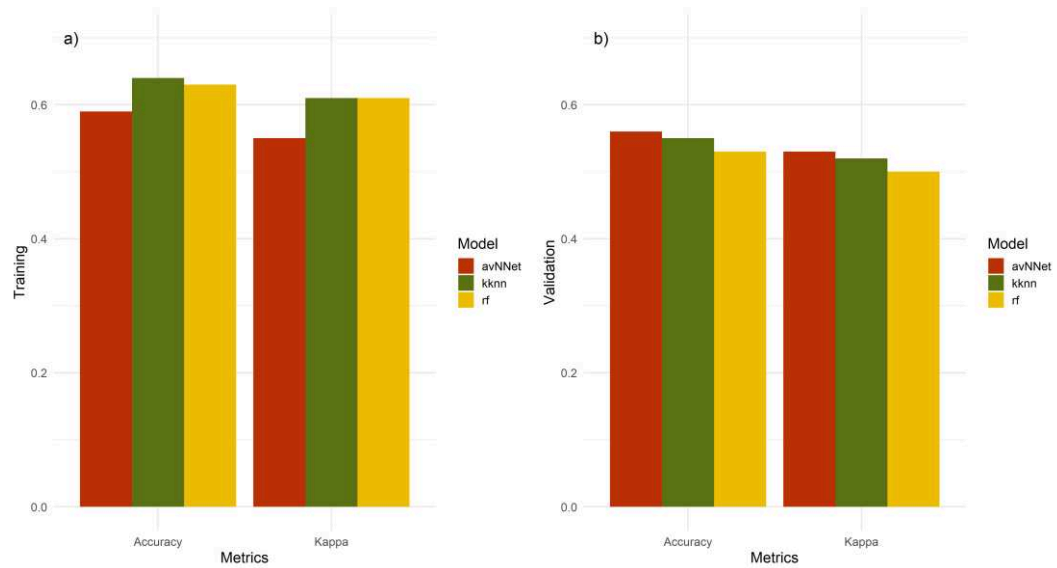


Fig. 5. a) Training and b) validation metrics (accuracy and kappa index) for the three classification models analyzed in Demay Point, King George Island, maritime Antarctica.

Table 2: Accuracy, kappa, sensitivity, and specific index values for the machine learning models analyzed.

Model		Training			Validation			Overfitting
		Mean	SD	CV	Mean	SD	CV	
avNNet	Accuracy	0.581	0.006	0.950	0.563	0.016	2.889	-0.018
	Kappa	0.553	0.006	1.064	0.534	0.017	3.250	-0.019
	Sensitivity	0.582	0.006	0.947	0.566	0.101	17.918	-0.016
	Specific	0.972	0.000	0.038	0.520	0.079	15.177	-0.452
kkn	Accuracy	0.639	0.004	0.687	0.547	0.011	1.99	-0.092
	Kappa	0.615	0.005	0.762	0.517	0.012	2.255	-0.098
	Sensitivity	0.637	0.004	0.695	0.494	0.071	14.269	-0.143
	Specific	0.976	0.000	0.030	0.524	0.067	12.871	-0.452
rf	Accuracy	0.608	0.004	0.779	0.536	0.010	1.951	-0.097
	Kappa	0.608	0.005	0.865	0.505	0.011	2.207	-0.103
	Sensitivity	0.631	0.004	0.778	0.528	0.082	15.511	-0.103
	Specific	0.975	0.000	0.033	0.495	0.072	14.555	-0.48

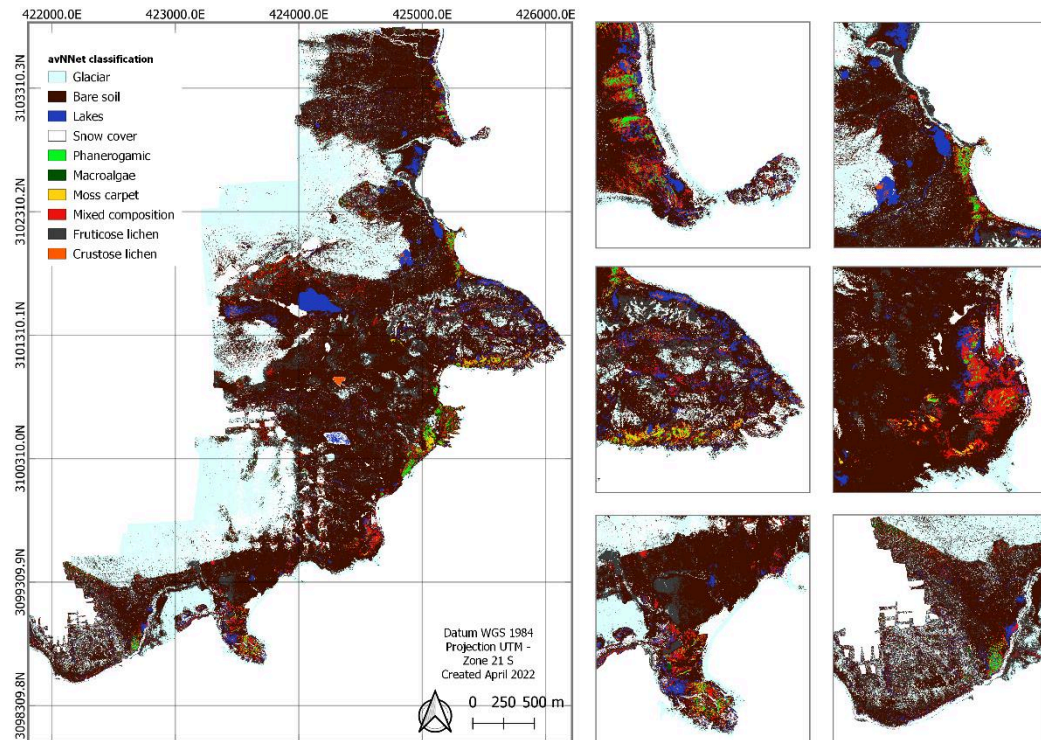


Fig. 6. Classification based on Model Averaged Neural Network – avNNet - algorithm utilizing 10 classes in Demay Point, King George Island, maritime Antarctica.

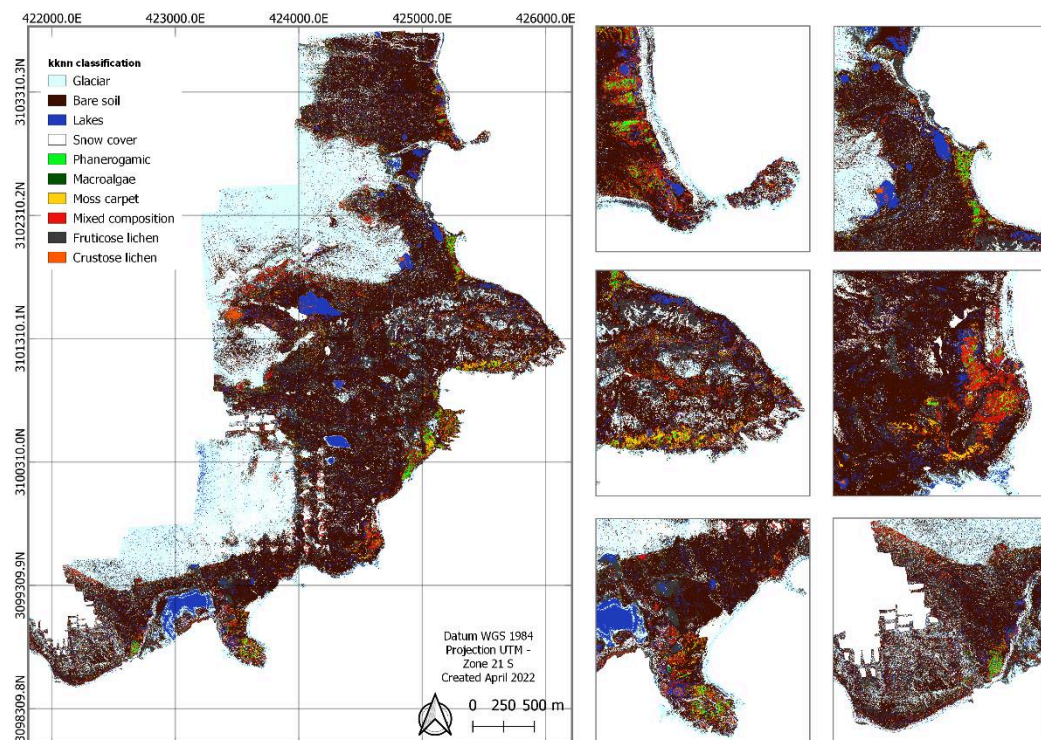


Fig. 7. Classification based on k-Nearest Neighbors – knn - algorithm utilizing 10 classes in Demay Point, King George Island, maritime Antarctica.

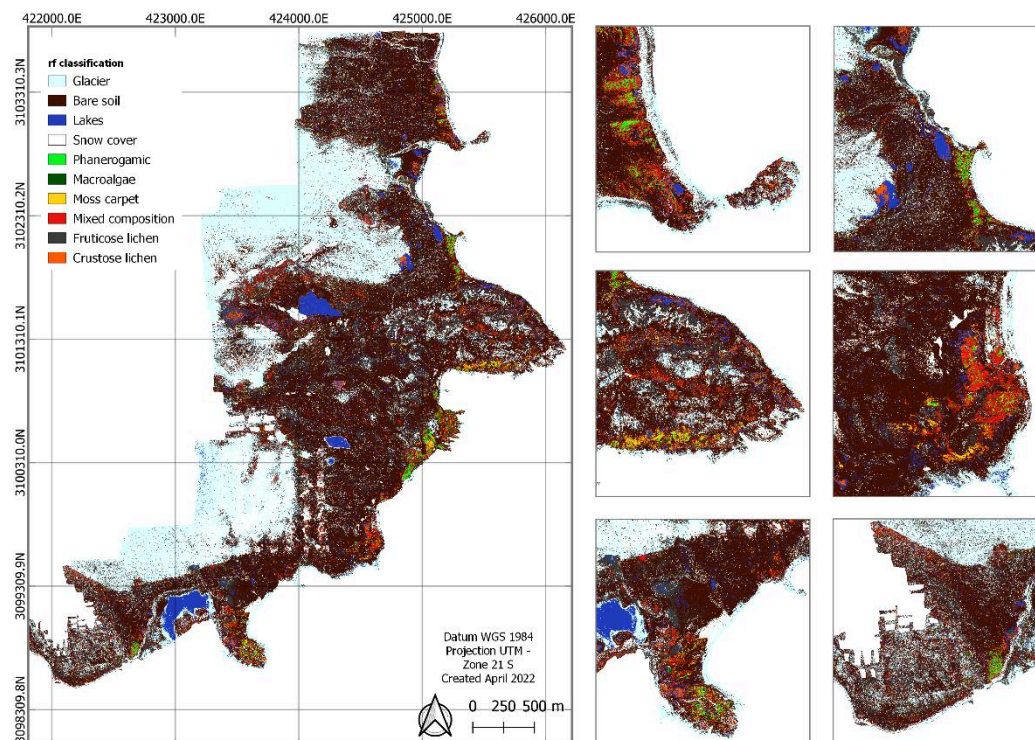


Fig. 8. Classification based on Random Forest - RF - algorithm utilizing 10 classes in Demay Point, King George Island, maritime Antarctica.

Considering the quantification of the classes in terms of area and cover percentage, the bare soil class occupies the largest area, corresponding to 62.41% of the total area in the manual classification. The total bare soil values decreased in the other classifications, corresponding to 45.89, 40.17, and 39.53% in avNNet, kknn, and rf, respectively. The total area measured was also lower in automatic classifications. In opposite, the macroalgae class occupies the smallest area, corresponding to 0.04% of the total area (Table 3).

Table 3: Total class area in km² in the four different classification methods in Demay Point, King George Island, maritime Antarctica.

Classes	Manual	Model classification			
		avNNet	kknn	rf	
		km ²			
Glaciär	2.02	2.23	2.13	2.33	
Bare soil	5.73	4.19	3.66	3.61	
Lakes	0.48	0.28	0.68	0.52	
Snow cover	0.59	1.03	1.10	0.98	
Phanerogamic	0.06	0.03	0.03	0.03	
Macroalgae	0.004	0.06	0.07	0.07	
Moss carpet	0.07	0.04	0.10	0.08	
Mixed composition	0.06	0.20	0.22	0.23	
Fruticose lichen	0.16	1.05	1.04	1.12	
Crustose lichen	0.01	0.02	0.08	0.16	
Total area	9.18	9.13	9.11	9.13	

The frequency of moda (Fig. 9) determines the absolute errors in the classification, where the increase in red points is visible, and thus, errors in the kkn and rf classifiers. In common, they all had difficulty classifying glacier areas. Based on the statistical analysis of accuracy and kappa (Fig. 5) and in the frequency moda (Fig. 9a) of models, we selected the avNNet algorithm as the best representative final map among the automated methods. In this way, we analyzed the values of variety error (Fig. 10a) and error 0-1 (Fig. 10b) just for avNNet algorithm, that supported the mistakes made in the front of glacier and lakes portions, in addition to the difficulty in classifying the areas where there was interference from snow cover and gaps in the capture of photos by the drone in the overflight.

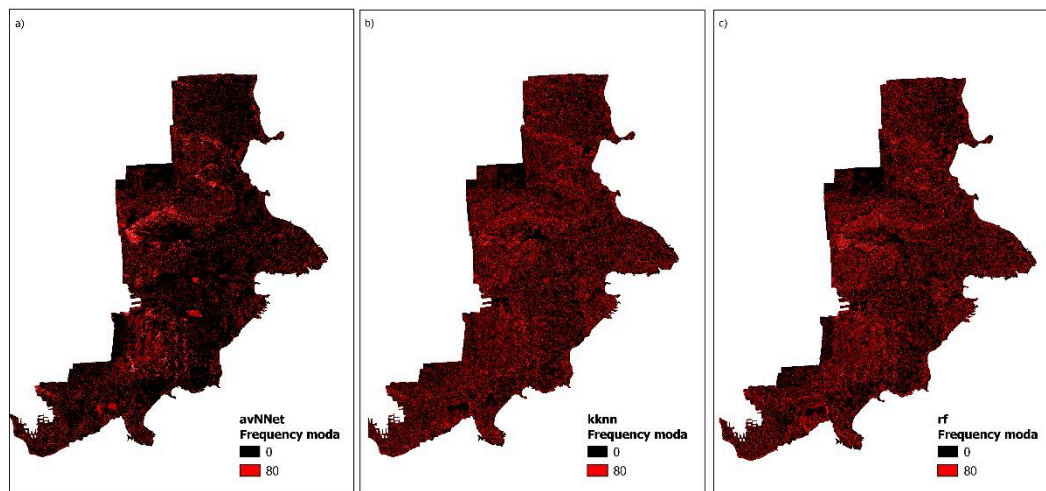


Fig. 9. Frequency moda results from three different classification models: a) avNNet - Averaged Neural Network; b) kkn - k-Nearest Neighbors; and c) RF – Random Forest in Demay Point, King George Island, maritime Antarctica.

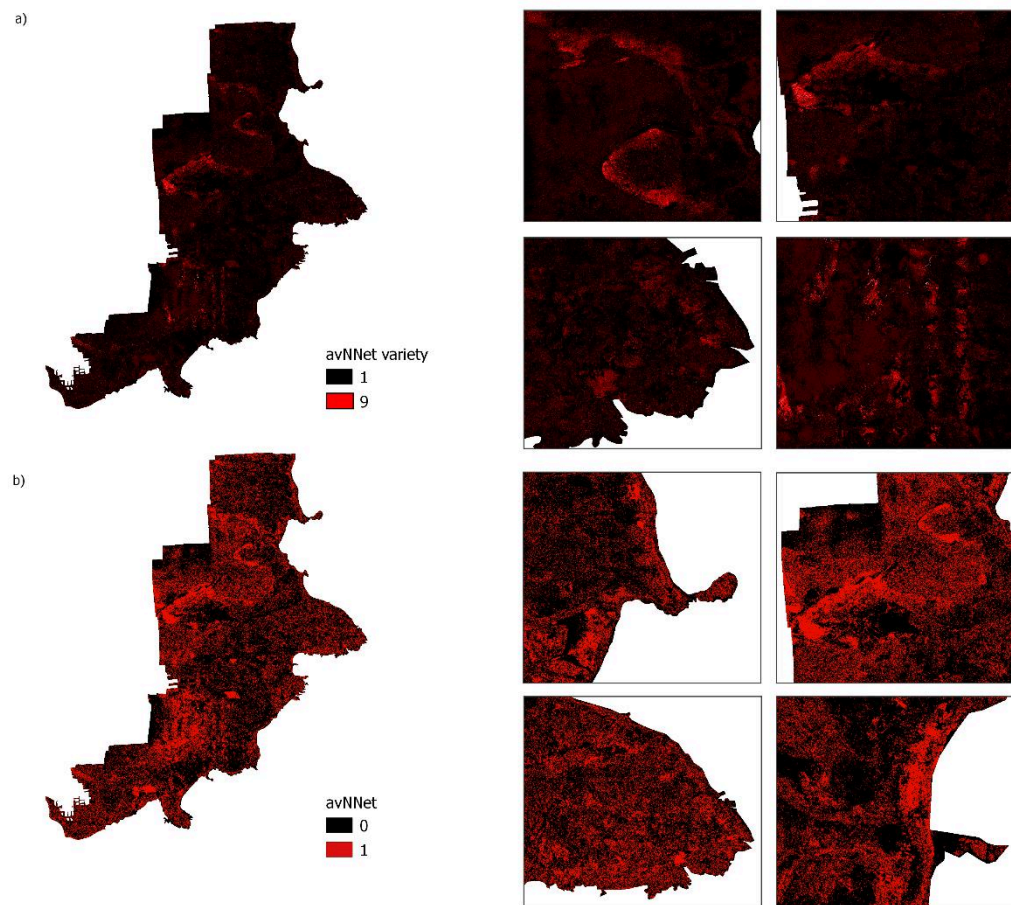


Fig. 10. Maps with a) variety error and b) 0-1 error, where 0 corresponds to correct predictions and 1 corresponds to an incorrect prediction from avNNet - Averaged Neural Network classification model to Demay Point, King George Island, maritime Antarctica.

3.3 GLACIAL RETREAT

The comparison between the images of different years obtained results of distances in meters of the retreat of the glaciers, and the total bare soil area in km². The measurement allowed the delimitation of the glacier front line in a large area. Failures were due to the shadows made by the snow cover during the period of capturing the images of an overflight, requiring an interpretation to help distinguish between the features of snow and ice. The orthophoto from 1954 wasn't possible to generate an orthomosaic, decreasing the total area available for measurement and totalizing 1.7 km² of the area without a glacier. Ice-free areas were mapped by polygons, based on the total area of the 2020 orthomosaic (Fig. 14).

Significant glacial variation has been detected in the area in over the years. Comparing the interval between 1956 and 2007, the bare soil increased 258.82% in 51 years, and increased by 9.84% in 13 years when reaching 2020 (Fig. 11). It represents 4.4 km² and 0.6

km² of the new area exposed respectively. Between 1956 to 2020 the bare soil increased 294.12% and it represents an increase of 5 km² in 64 years.

Sphinx Glacier, despite being little represented in the orthomosaic, there was already exposed soil in front of the glacier in 1956. This area increased by 601.69 m in 2007 (Fig. 12) and advanced another 83.83 m in the period between 2007 and 2020 (Fig. 13). Resulting in a total retreat of 685.52 m (Fig. 11). The aerial photo from 1956, showed that the entire front of the Baranowski Glacier was covered by the glacier (Fig. 11). Over the years, the retreat of Baranowski provided a total of 502.53 m in 2007, increasing to 777.63 m in 2020 (Fig. 12). The retreats of the Tower and Thawing Glacier presented increases in 713.02 and 226.02, respectively, during the period 1956-2007, adding 163.48 and 302.41 meters, respectively, when reaching 2020. Thus, the total size of the retreat in the period 1956-2020 was 876.5 meters in the Tower Glacier, the second-largest retreat measured, and 529.43 meters in the Thawing Glacier. Finally, the Windy glacier was the one that regressed the greatest distance, when in 1956 it approached the beach line (Fig. 11). Windy retreated 802.89 meters during the period 1956-2007, losing more 182.01 meters until 2020 (Fig. 13). In total, the retreated was 984.9 meters in 64 years (Fig. 14).

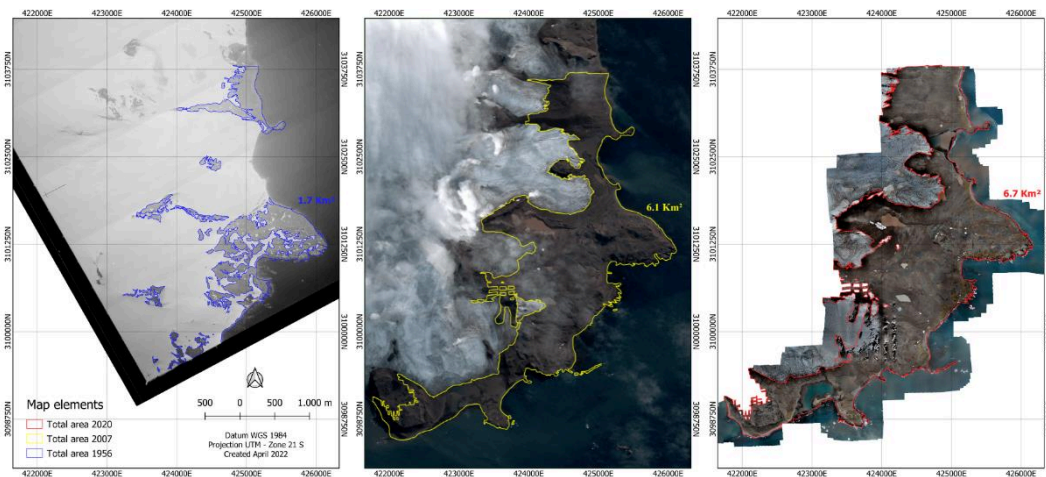


Fig. 11: Demay Point, King George Island, and adjacent areas. a) Aerial photo by British Antarctic Survey corresponding to the 1956 year; b) Quick bird satellite image from 2007; and c) Orthomosaic created from drone images in the year 2020.

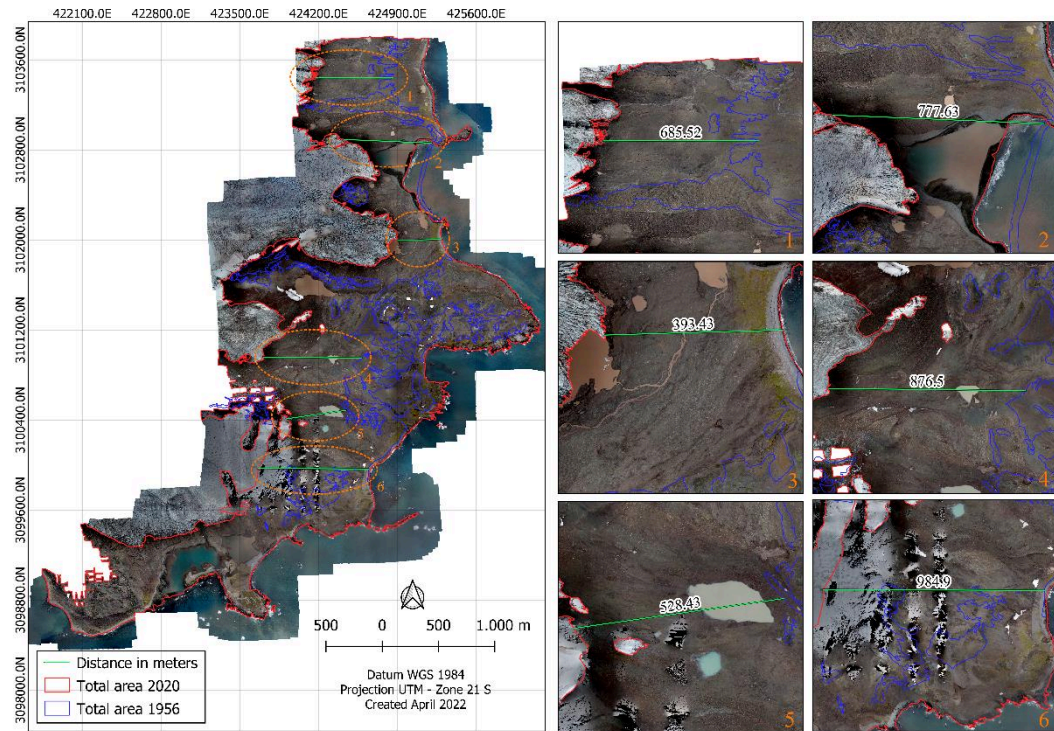


Fig. 12: Orthomosaic with polygons corresponding to the variations in front of glaciers in the region of Demay Point, King George Island, and adjacent areas during the years 1956 and 2020. 1. Sphinx Glacier; 2-3. Baranowski Glacier; 4. Tower Glacier; 5. Thawing Glacier; 6. Windy Glacier.

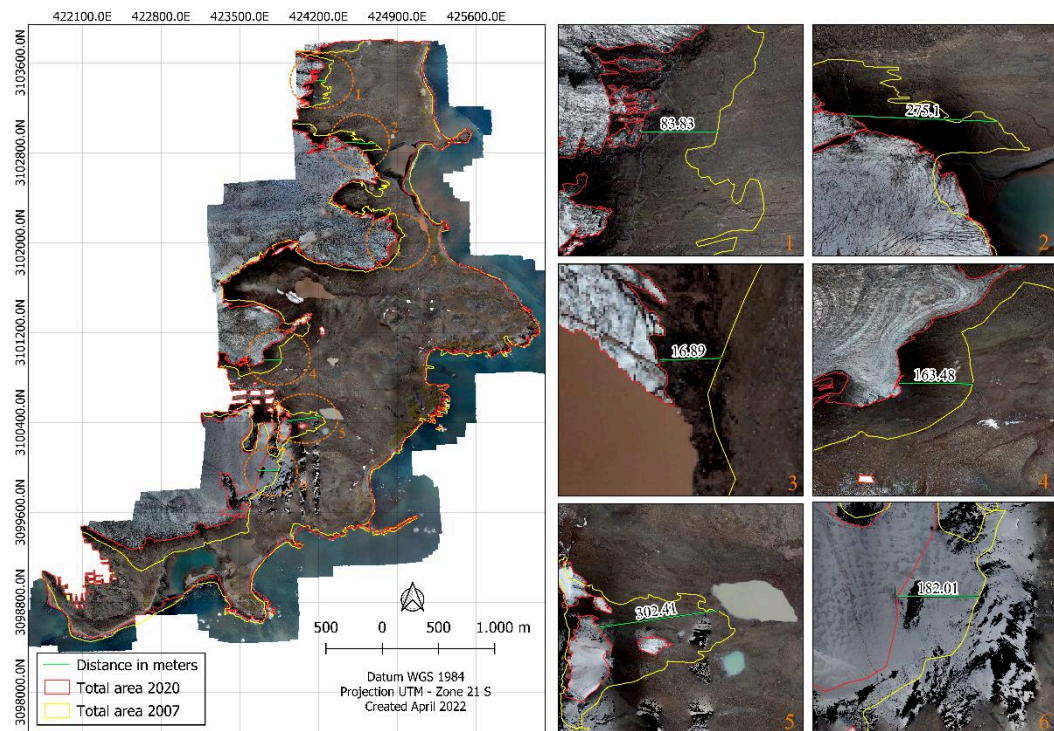


Fig. 13: Orthomosaic with polygons corresponding to the variations in front of glaciers in the region of Demay Point, King George Island, and adjacent areas during the years 2007 and 2020. 1. Sphinx Glacier; 2-3. Baranowski Glacier; 4. Tower Glacier; 5. Thawing Glacier; 6. Windy Glacier.

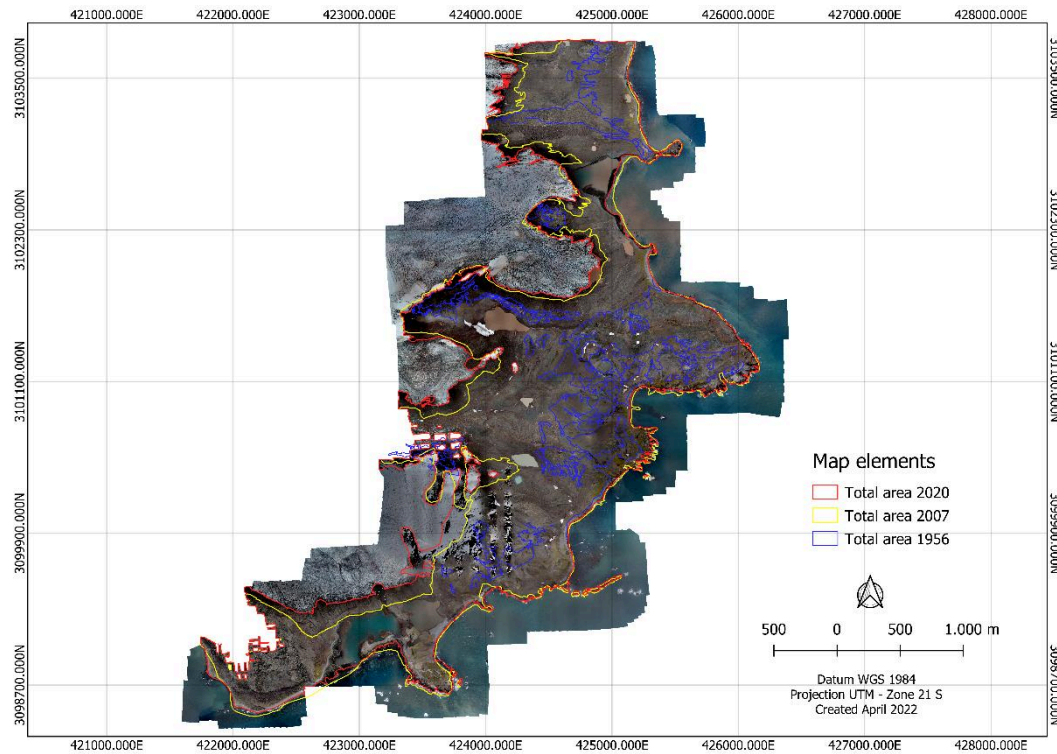


Fig. 14: Orthomosaic with polygons corresponding to the variations in front of glaciers in the region of Demay Point, King George Island, and adjacent areas during the years 1956, 2007, and 2020.

4. DISCUSSION

4.1 PERFORMANCE OF MACHINE LEARNING ALGORITHMS

Despite the mixed vegetation communities in Antarctica, and the difficulties in classifying dominated pixels with mid-resolution satellite images (Casanovas et al., 2015), his study demonstrated the benefits of vegetation mapping through high-resolution images, in addition to support automatic classification algorithms through pixel training and validation, combined with field sampling efforts. The ultra-high-resolution up to a few mm/pixel of the images captured and the fairly large coverage that they can provide, permit distinguishing many details related to the vegetation not evident in satellite imagery, namely about their Antarctic communities (Miranda et al., 2020). Considering the vegetation as the target of interest in the mapping, the best results were obtained by the Averaged Neural Network – avNNet classifier due to the high accuracy of this model. This classification result contradicts studies by Siqueira et al. (2022) that obtained better performance with different models (C5.0 and rf) than avNNet to classify Antarctic geomorphology, but agreement with (Meyer, 2017) to predict rainfall rates.

The number of predictor classes cannot be greater than 10, due to the attributes in recent studies showing low or almost zero predictive capacity in different spatial resolutions, which

the authors associated with the excess of details that can generate a lot of noise, and result in losses in explanatory power (Cherkassky and Ma, 2004; Sena et al., 2020). Therefore, we limited to a few communities in an attempt to encompass all representative plant formations.

Unlike other studies with high numbers of training and validation repetitions (Silveira et al., 2022), our study used only 20 repetitions due to the high degree of resolution of the orthomosaic, where the capacity of the machines did not support the increase in repetitions and thus, the accuracy of the predictions.

The area of the classes showed different total sizes between the classifier and the manual maps. The macroalgae, for example, had an increase in coverage in the other classifications but is possible to visualize that the classifier avNNet marked macroalgae in the region of glaciers (Fig. 4). This occurrence is not only impossible due to the extreme not vegetated proglacial environments (Slaymaker, 2009), but also due to the close association of *Prasiola crispa* (Lightfoot) Menegh. with ornithogenic areas (Kovacik and Pereira, 2001), concentrated near the coast.

Differences in manual classification for automatic models can be seen as errors when analyzed at the first instance. However, when compared with the study by Pereira et al. (2010), it can be noted that the region of Demay Point, has a greater diversity of classes through the authors' classification. The same area has a greater predominance of fruticose lichens in our manual mapping (Fig. 3) and visualized in the field, but due to the lack of release of phytosociological points in this portion, we couldn't prove this greater diversity. In this way, automatic classification can be more efficient in distinguishing classes that were visually not possible to identify manually. However, we must emphasize the classification of lakes and glaciers in this region, mainly by avNNet and kkn, where it is distant from the glaciers, without drainage line, and also a high altitude region.

Manual classification allowed all remaining areas not classified as vegetation or glacier/snow cover to be classified as bare soil. Thus, this class took a total homogenization, not assuming microtopographic differences. When classified automatically, this class gains several points that transform it into other categories. This may be due to the heterogeneity that makes up these areas of exposed soil, whether by rocks, different soil colors, nests of seabirds, and even difference between the pebbles of the beach line. These attributes were not included in the training, as they would represent an increase in the number of classes. Thus, these variations confused the classifiers. The high resolution of the image promoted a differentiation in the glaciers due to the marks of the cracks, giving a coloration in brownish

tones and thus, being classified as other classes. On avNNet these differences were less pronounced than the other algorithms.

4.2 GLACIAL RETRAT SCENARIO

Measuring the area of retreat of glaciers from the orthomosaic launches a new perspective for monitoring the region. When comparing with other images from previous years, we show that in 64 years (period between 1956 and 2020) the region lost an ice area of 5 km², corresponding to an increase in retreat rate of 0.14 km² year⁻¹. The Windy Glacier was the most the hardest impacted, even retreating in 984.9 m per year, a total of 15.38 meters year⁻¹. Given this scenario of glacier retreat in this portion of the KGI, it is important to keep this temporal vegetation mapping database updated, to monitor and assess future vegetation changes in maritime Antarctica. Chown et al. (2015) highlighted the large transformation that the new tools development will mean in understanding Antarctic biodiversity over the next 20 years. Since the distribution of plant communities is determined by environmental factors such as temperature (Convey and Smith, 2006), moisture availability (Kennedy, 1993), and microtopography (Schwarz et al., 1992; Melick & Seppelt, 1994a), new ice-free areas could provide new conditions for vegetation expansion (Quartino et al., 2013; Smith, 2001). Moisture could change processes when poorly drained areas become well-drained, soil temperature tends to increase and vegetation characteristics are altered, like CO₂ ecosystems variability (Thomazini et al., 2016).

According to Petsch et al. (2019), the vegetation area mapped in the Fildes peninsula had a growing from 1.5 to 2.73 km² during the 1986-2016 period, highlighting the moss growth. The authors expect vegetation growth in this region in the coming years, with continued retraction of the Collins Glacier and increased availability of liquid water in the system. Calvet et al., (1999) revealed through satellite images that the area of the Livingston Island ice cap decreased by 4.31% from 1956 to 1996, and assigned to local factors, mainly topographic, the influence on advances and retreats of the ice front. In KGI, Sziło and Bialik (2018) found that since the early 1980s the Baranowski glacier has terminated on land, and the front position of the Baranowski Glacier has changed considerably over the last 60 years. The authors measured the highest recession rate during 2001-2003, which reached 65 m/year retreats. Birkenmajer (2002) demonstrated the Ecology Glacier retreat, under continuous recession at least since 1956/1957, but the rate decreased in 1988/1989, amounting to 4–4.5 m per year. It rapidly accelerated in the past decade (1989–1999), reaching a rate of up to 30 m

per year. The author expanded the same situation to Windy and Baranowski Glaciers. (Pasik et al., 2021) measured the front glacier in the same region as this present study, and found that during the period between 1956 and 2015, there was a significant recession of the glaciers fronts and a decrease in their thicknesses. Then until 2001, the glacier's front receded by 200–400 m, and between 2007 and 2013 the front receded by 50–100 m. The authors attributed these to climate changes, where the mean air temperature increased $0.019\text{ }^{\circ}\text{C a}^{-1}$ during the 1948-2011 period (Kejna et al., 2013; Pasik et al., 2021).

5. CONCLUSION

Multipli methodologies to obtain high classification accuracy of ice-free areas in Antarctica are presented. The proposed method of the avNNet classification algorithm is relevant given the very low complexity and computational costs given the high efforts required by Antarctic environments. However, the manual classification still presents greater condensation of plotted vegetation classification results. The high specificity of Antarctic vegetation and subjective changes in microtopography are challenges when applying classification techniques in this region. Machine learning is a tool capable of filling these gaps, but it must be associated with certain characteristics faithful to the landscape. Thus, we consider that, even with the high accuracy of the Averaged Neural Network (avNNet) algorithm, among the tested algorithms, there are difficulties in predicting similar structures such as the high resolution in relation to the exposed soil of the glacier retreat and confounding the predictor when predicting the study attributes, the vegetation. Under the current scenario of climate change, these results acquire high relevance as they suggest that the ice-free areas increased 5 km^2 in 64 years, and demarcates the vegetated sites, providing a large data for future monitoring of the vegetation colonization scenario in these ice-free portions of King George Island.

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CONCLUSÃO GERAL

O presente trabalho abordou sobre frentes de variáveis espaço-temporais às comunidades vegetais da Antártica. A disposição, composição e diversidade dessas comunidades singulares, acrescentadas à dados de solos, microrganismos e produção de gases, promove o entendimento da interação complexa entre os ambientes terrestre e atmosférico. Quando visto em um cenário de tempo passado, os estudos dos recuos de geleiras dão luz à um maior significado para as mudanças climáticas e estimativas futuras.

Nossos resultados mostraram comportamentos distintos entre comunidades vegetais e a produção de gases do efeito estufa, mas uma tendência geral de aumento de produção com o aumento da temperatura. À -2 °C algumas áreas atuaram como dreno de N₂O demonstrando o impacto das condições de baixas temperaturas ao contribuir para os estoques de N do solo. Os carpetes de musgos, maiores em biomassa na Antártica Marítima, tiveram as maiores emissões de CH₄, contrastando com os menores valores de produção de CO₂. Os líquens fruticosos, localizados no topo da área estudada, provaram ser bons drenos de CH₄, porém, com os maiores valores de emissão de CO₂. Enquanto os solos nus, com seus baixos valores de matéria orgânica, promoveram os melhores drenos de CO₂ acima de 6 °C. Dessa forma, essas topossequência demonstra a fundamental importância do monitoramento do solo e da vegetação na compreensão do papel das comunidades vegetais antárticas como sensíveis indicadoras de mudanças climáticas locais.

O estudo com sequência temporal na Antártica atuou como uma grande amostra dos padrões de produção de troca líquida de CO₂. Ao variar conforme o tipo de cobertura vegetal e a posição na paisagem, foi possível compreender também o papel das comunidades microbianas e a disponibilidade de fósforo como interferências nessa produção. Assim, o local com maior deposição de matéria orgânica, maior diversidade microbiana do solo e com ausência de cobertura atual mostrou os maiores valores de CO₂ emitidos, enquanto somente a área com diversidade de espécies vegetais promoveu o efeito de dreno de CO₂ na região estudada.

Ao abordar uma escala local, a partir do estudo de amostras espacialmente localizadas, determinamos a filtragem de habitat moldando a variabilidade da diversidade das comunidades vegetais na Antártica Marítima. A variação apresentada neste estudo em relação à riqueza de espécies dos afloramentos rochosos sob influência de Petrel-Gigante foi melhor prevista por um modelo linear que incorporou influências abióticas e bióticas do ambiente.

Assim, reforça-se a necessidade da preservação desse ecossistema, onde distúrbios em suas propriedades e na população das aves voadoras podem conduzir à uma menor riqueza das espécies vegetais.

Diante do grande esforço amostral que é o estudo da Antártica, mapeamentos a partir de técnicas de *machine learning* demonstraram ser grandes aliados ao estudo botânico. Nosso estudo realizou diferentes técnicas de mapeamento e preditores, classificando uma extensa área em comunidades vegetais, áreas de geleiras e áreas de solo exposto em que o preditor avNNet apresentou melhor acurácia. Porém, alguns locais divergiram da classificação manual devido à alta resolução da imagem e a necessidade de utilizar poucas classes de treinamento. Mensurar as áreas de recuo de geleiras é um monitoramento que deve ser constante. A partir do nosso estudo, foi possível comparar imagens temporais e constatar um aumento de recuo de 5 km² em 64 anos na região, promovendo importantes dados para o cenário futuro de colonização vegetal dessas áreas.