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ECOSYSTEMS

Potential greenhouse gases emissions by different plant communities in maritime Antarctica

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Abstract: 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 N_2O production potential was associated with the Phanerogamic Community under the strong ornithogenic influence (phosphorus, nitrogen, and organic matter contents). Seven different areas acted as N_2O 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 CH_4 emissions and low CO_2 production potential. Fruticose Lichens had a CH_4 sink effect and the highest values of CO_2. The low rate of organic matter provided the CO_2 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.

Key words: Antarctic vegetation, climate changes, cryptogamic communities, greenhouse gas production.

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 CO_2 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 (CO_2), methane (CH_4), and nitrous oxide (N_2O) 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 CO_2-C emissions. Zdanowski et al. (2005) reported that increased microbial activity may be expected in Antarctic areas where CO_2 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 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.

MATERIALS AND METHODS

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; Supplementary Material - Figure S1).

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.

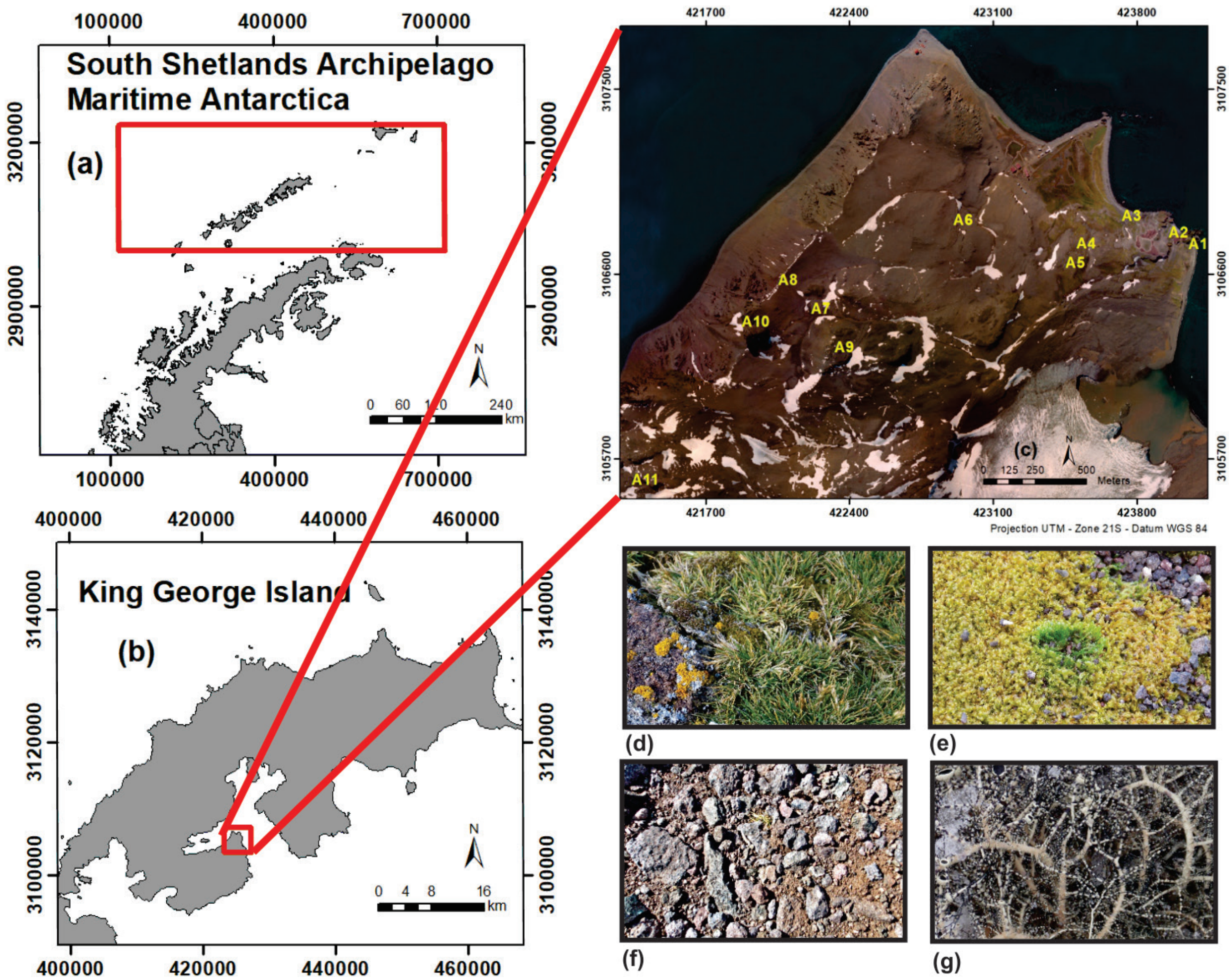

Figure 1. Map of the South Shetlands Archipelago (a), showing the location of King George Island (b) and the studied area near the Polish Henry Arctowski Station (c). Areas 1, 2, and 3: Phanerogamic Community (d); Areas 4 and 7: Moss Carpet Community (e); Area 8: Bare soil (f); Areas 9, 10, and Area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

Soil sampling

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 (H_2O), P, K, Na, Ca, Mg, Al^{3+}, total acidity (H +Al), bases sum (BS), effective cation exchange capacity (CECeff), 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.

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, identified in plastic bags and sent to the University of Minnesota - USA for the incubation study.

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-days 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 O_2 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-days period was allowed for the soil to equilibrate after rewetting (Thomazini et al. 2015a, Fierer & Schimel 2003, Franzluebbers et al. 1996).

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 CO_2, N_2O, and CH_4 production potentials were analyzed by the means of triplicate samples, for different temperatures. The N_2O 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 (CO_2e) was calculated to describe different GHG in a common unit and mean the amount of CO_2 which would have the equivalent global warming impact (GWP) (IPCC 2007). The CO_2e 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).

RESULTS

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 SI). 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. Desv. and *Sanionia* spp., which were recorded in five areas; there, *D. antarctica* and *Sanionia* spp. possessed high IES values (Table SII).

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 values of carbon dioxide equivalent, for N_2O and CH_4, were converted and showed in the Table SIII.

The highest N_2O production potential was associated with the Phanerogamic Community - *Deschampsia* – *Prasiola* association (area

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	*Deschampsia - Prasiola*
2	5	Phanerogamic	*Deschampsia - Colobanthus*
3	20	Phanerogamic	*Deschampsia - Syntrichia*
4	80	Moss Carpet	*Sanionia - Bryum*
5	83	Phanerogamic	*Deschampsia - Sanionia*
6	85	Fruticose Lichens	*Usnea - Andreaea*
7	90	Moss Carpet	*Sanionia - Bryum*
8	220	Bare soil	-
9	260	Fruticose Lichens	*Usnea - Schistidium*
10	280	Fruticose Lichens	*Himantormia - Usnea*
11	300	Fruticose Lichens	*Usnea - Schistidium*

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.

1), under strong ornithogenic influence, near the coast (3 m a.s.l), followed by the also Phanerogamic area 3 (Figure 2a). 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 N_2O production pattern was observed with different temperatures, with a maximum value observed at 6 °C (22.58 ng N g_{soil}^{-1} day^{-1}) (Figure 5a). On the other hand, seven distinct areas acted as an N_2O sink at a temperature of -2 °C, demonstrating the influence of low soil temperatures contributing to store N in soils.

The PCA shows N_2O values strongly correlated with 6 °C ($r = 0.95$; $p < 0.05$), where axis 1 explains a total of 74.6 % of the variance (Figure 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 ngN g_{soil}^{-1} 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 N_2O 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.

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

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

Chemical properties	Areas										
	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
Ca^{2+}	4.81	3.66	7.07	2.15	2.03	17.19	25.36	16.54	7.43	10.94	22.39
Mg^{2+}	1.49	2.08	2.14	0.77	1.50	9.95	14.10	8.23	8.11	9.69	11.86
Al^{3+}	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	22.10	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 (H_2O); 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}); Al^{3+}: 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).

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 BS 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).

Results suggested that there is an overall trend on CO_2 production potential with increasing temperature (Figure 4a). The bare soil (area 8) was the only studied area with negative values, considered as a CO_2 sink (-0.08, -0.22, and -0.17 ug C g_{soil}^{-1} 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 ug C g_{soil}^{-1} day^{-1}) (Figure 5c), demonstrating the influence of very high temperatures on CO_2 production potential in the Antarctic soils. The Moss Carpets remained with low production potential at all temperatures. Although, the moss floristic composition can

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

Physical properties	Areas										
	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

[a]SBCS; [d]IN SPA/MAPA 02/2008.

Table V. Average values of production potentials of N_2O (ngN g_{soil}^{-1} day^{-1}), CH_4 (ngC g_{soil}^{-1} day^{-1}), and CO_2 (ugC g_{soil}^{-1} day^{-1}) in different plant communities along a toposequence.

Temp.	-2 °C			4 °C			6 °C			22 °C		
Site	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	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

also be considered a factor that contributes to the CO_2 source strength.

Greater CO_2 production potentials (Figure 4a) were observed at the highest positions of the toposequence at 22 °C (areas 9, 10, and 11 - 260 to 300 m a.s.l), with a maximum in area 9 (Figure 5c), under Fruticose Lichens Community (22.08 µg C g_{soil}^{-1} 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).

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 ugC $g_{soil}^{-1}$$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, OM, 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).

Table VI. The sensitivity of the responses to GHG concentrations with temperature increase. N_2O: ngN g_{soil}^{-1} day^{-1}; CH_4: ngC g_{soil}^{-1} day^{-1}; CO_2: ugC g_{soil}^{-1} day^{-1}.

Temp.	-2 °C→4 °C			-2 °C→6 °C			-2 °C→22 °C		
Site	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	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

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 CO_2 sink potential for the region and a great CH_4 source. On the other hand, Fruticose Lichens Communities showed a CH_4 sink potential. In this study, floristic composition did not significantly affect N_2O and CO_2 sources, whereas lichens and phanerogams tended to act as a source with higher temperatures.

The lower moist community, at area 1, showed N_2O 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 N_2O 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 N_2O 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 N_2O sinks even at higher temperatures (0.02 mg N_2O m^{-2} h^{-1} at 22 °C). These authors suggest that since soil total organic C and total N were extremely low, a very N_2O efflux is expected.

Zhu et al. (2014b) observed the N_2O sinks generally occurred at waterlogged areas

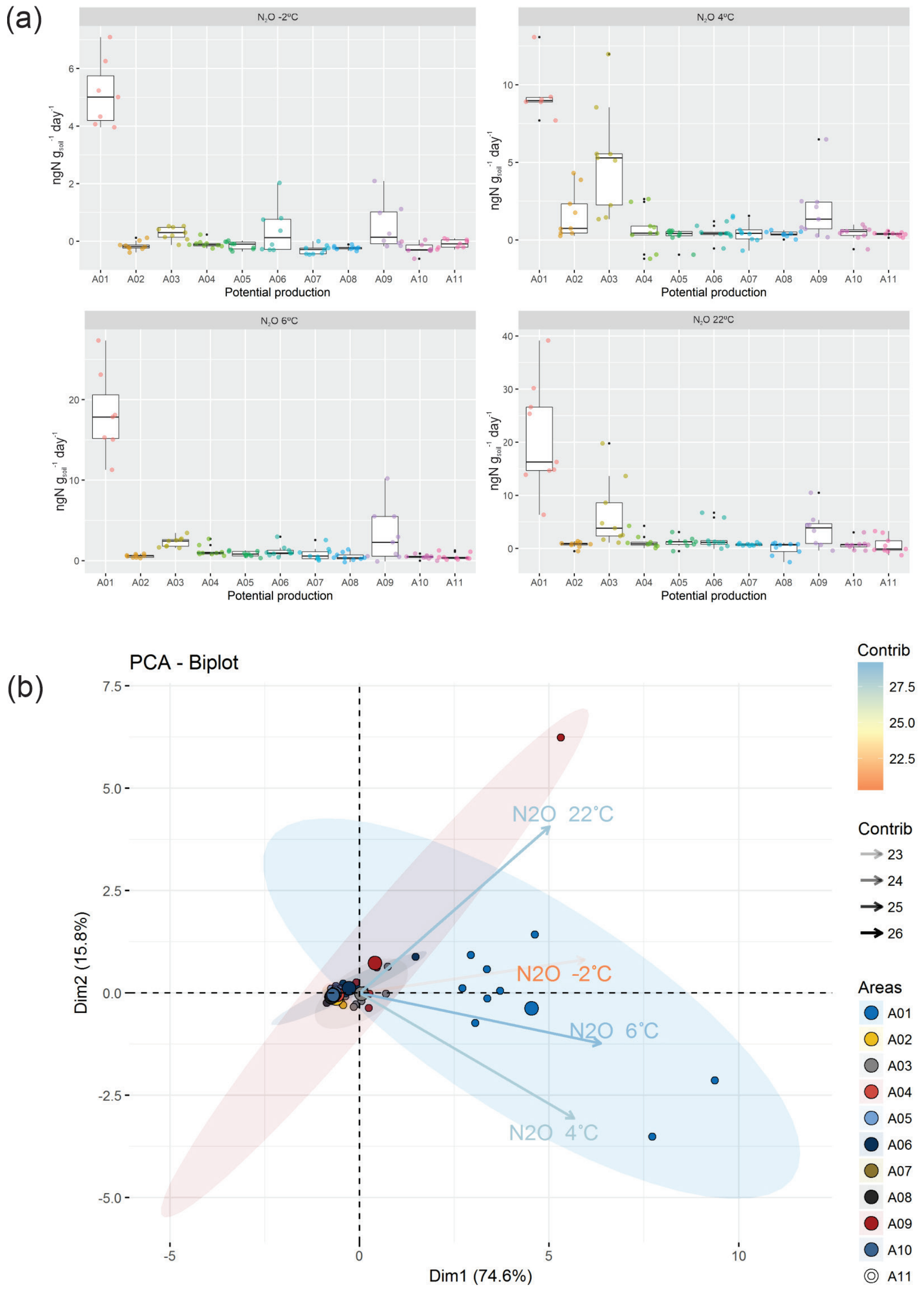

Figure 2. Average values of N_2O production potential at -2, 4, 6, and 22 °C, in 11 areas sampled along a toposequence (a). Principal component analyses - PCA indicating good discrimination and grouping of plant communities according to the N_2O soil production values, at temperatures of -2 °C, 4 °C,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

(-3.0 ± 1.2 μg N_2O m^{-2} h^{-1}) where water table is an important driver of GHGs fluxes, while dry and mesic marsh areas presented weak or strong N_2O sources (41.6 μg N_2O m^{-2} h^{-1} and 2.2 μg N_2O m^{-2} h^{-} 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 N_2O sink effect.

The Moss Carpets Communities (areas 4 and 7) experiences distinct soil moisture conditions and both showed the largest CH_4 production

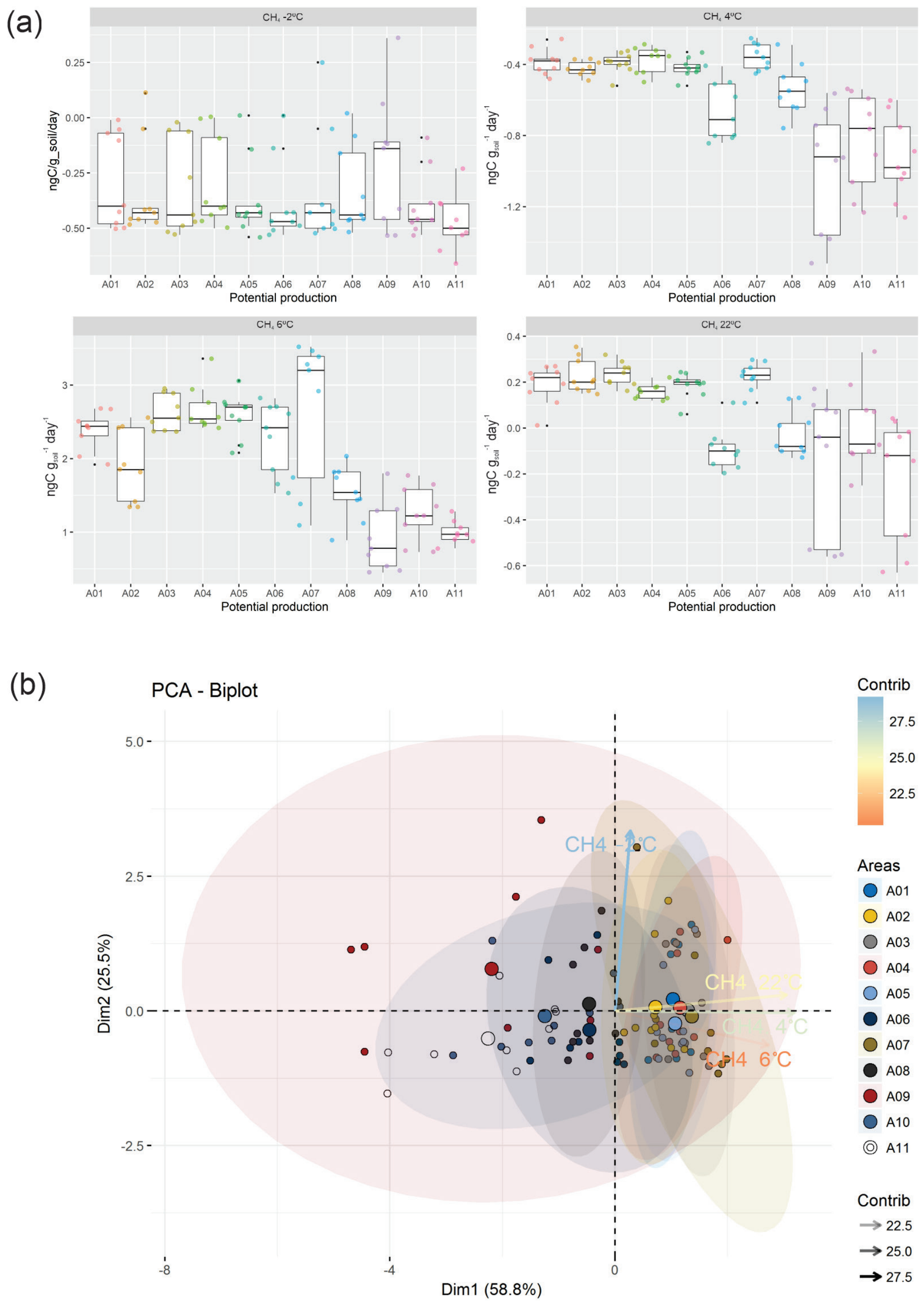

Figure 3. Average values of CH_4 production potential at -2, 4, 6, and 22 °C, in 11 areas sampled along a toposequence (a); Principal component analyses - PCA indicating discrimination and grouping of plant communities according to the CH_4 soil production values, at temperatures of -2 °C, 4 °C, 6 °C, and 22 °C (b).

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 CH_4 rates was expected since the current anaerobic conditions in area 7 would restrict methanogenic activity (Vieira et al. 2013). Despite the same CH_4 production values, they were not grouped by soil properties. Zhu et al. (2014b) registered a great temporal variation in CH_4 fluxes from tundra areas in maritime Antarctica, where high CH_4 uptake

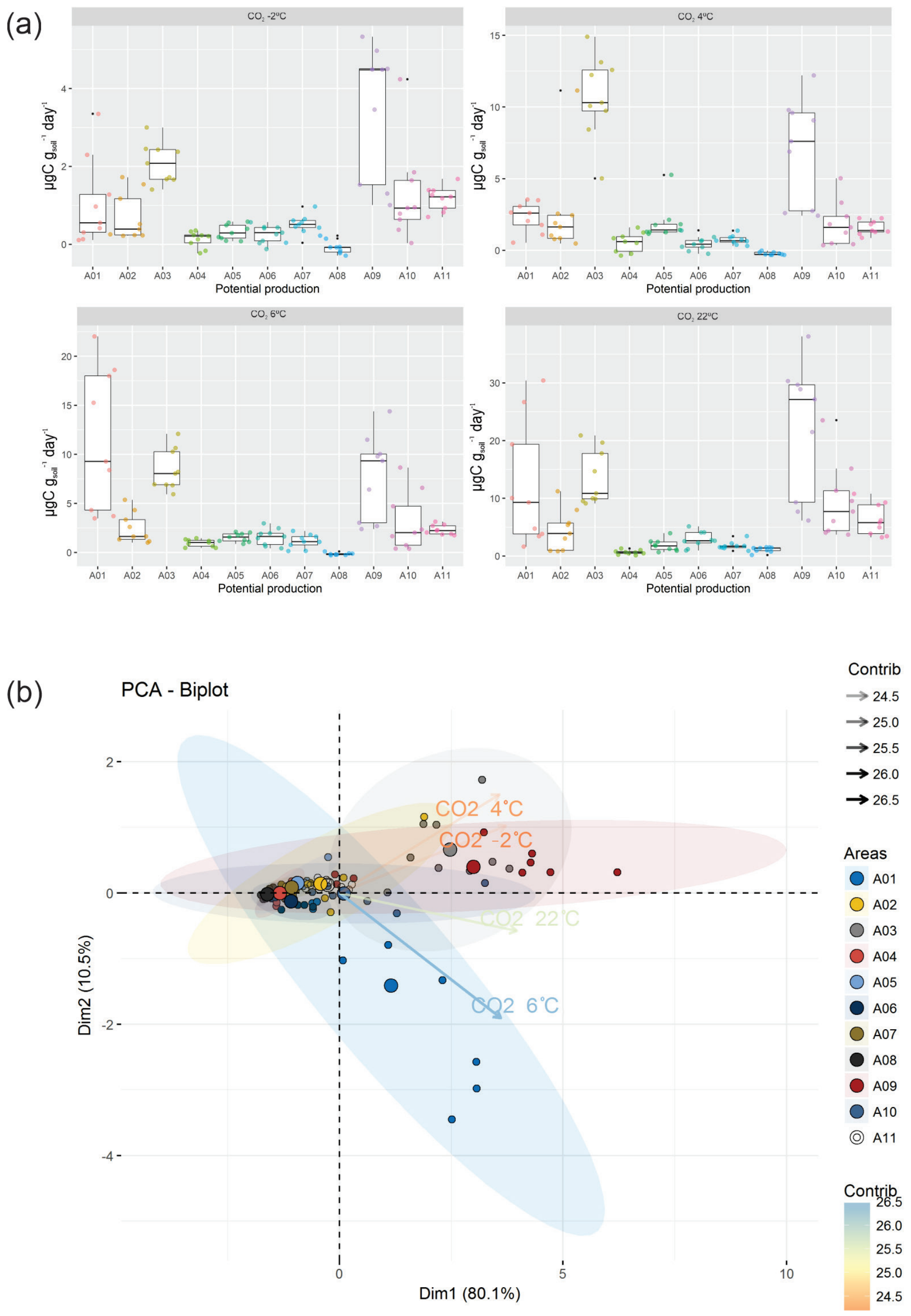

Figure 4. Average values of CO_2 production potential at -2, 4, 6, and 22 °C, in 11 areas sampled along a toposequence (a); Principal component analyses - PCA indicating discrimination and grouping of plant communities according to the CO_2 soil production values, at temperatures of -2 °C, 4 °C, 6 °C, and 22 °C (b).

mainly occurred at a relatively dry area (27.7 ± 5.0 µg CH_4 m^{-2} h^{-1}).

Even considering these Antarctic ecosystems a CH_4 sink at normal local temperatures (-2 °C), with increasing temperatures (4 °C) (Table V), we further detect a CH_4 production potential (warming) including waterlogged areas, with increased sensitivity of CO_2 at 6 and 22 °C (Table VI). The same CH_4 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 CH_4 emissions were recorded at 6 °C, however there was a drop in

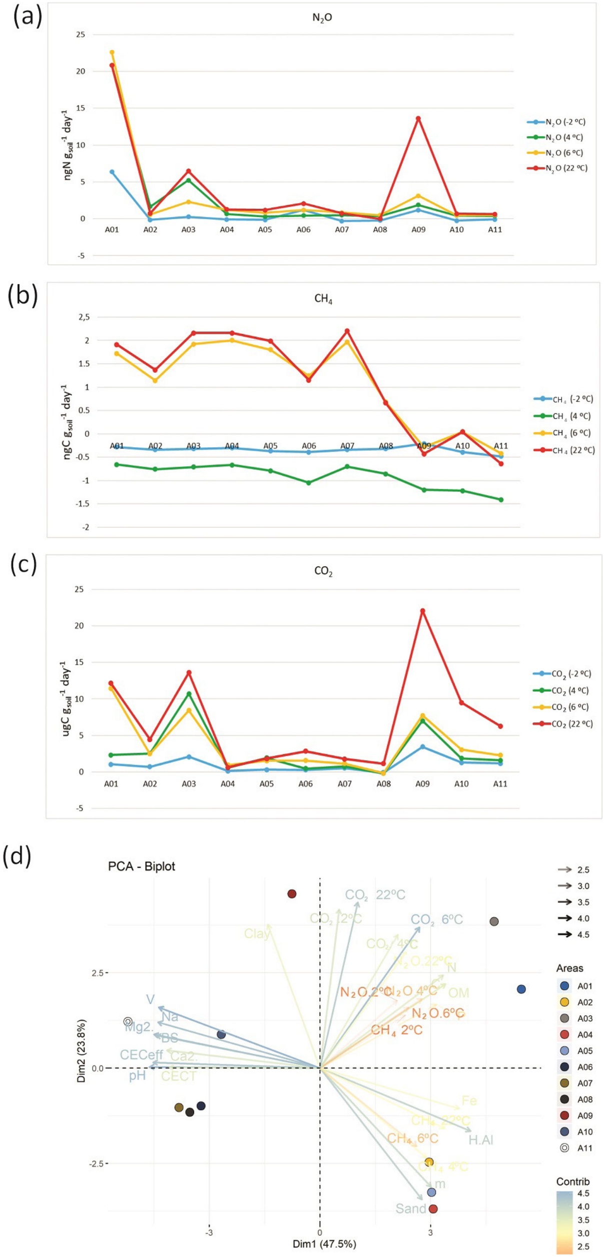

Figure 5. a) N_2O, b) CH_4, c) CO_2 soil production values, at temperatures of -2 °C, 4 °C, 6 °C, and 22 °C for 11 areas analyzed, and d) PCA for main soil properties and GHG potential production.

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 CO_2 sensitivity with the actual influence of animal colonies (area 1) and the CO_2 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 CO_2 exchanges (Zhu et al. 2014a). Increased microbial activity is expected to increase soil organic matter and consequently enhances soils CO_2 production potential from maritime Antarctica (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 CO_2 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 CO_2 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 CO_2 production potential (temperatures of -2 °C and 22 °C). Even with a vegetation cover dominated by lichens and sparse mosses (Table SII), area 9 shows great amount of organic matter (2.87 dag/kg - Table III). Therefore, this was a determining factor for the high CO_2 production potential in the area 9.

This OM influence is also evident when analyzing the area with the highest CO_2 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 CO_2 sink in the toposequence (Figure 4a). In general, the presence of vegetation cover favored a higher CO_2 sink strength, notably where cryptogamic communities had low OM contents. Increasing CO_2 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 CO_2 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 CO_2 production potentials under vegetated soils than non-vegetated, while the N_2O potential did not differ between both areas. The CO_2 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 CO_2 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, CO_2, 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 CO_2 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, O_2 consumption and CO_2 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 CO_2 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.

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 CO_2 source with lower potential of GHG emissions and act as a CH_4 source, specially under warming conditions.

4. Fruticose Lichens Communities at the higher parts of the toposequence showed a CH_4 sink potential.

5. Areas with greater biological influence presents higher N_2O and CO_2 production potentials, especially due higher N, OM, and low soil pH, increased microbial activity, and sandy texture, resulting in a decrease of N_2O mineralization rate.

6. N_2O and CO_2 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 N_2O 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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SUPPLEMENTARY MATERIAL

Tables SI-SIII

Figure S1

How to cite

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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.