

SOIL ORGANIC MATTER MINERALIZATION AND TRANSFORMATION IN INNER SHELF OASES OF EAST ANTARCTICA: LABORATORY ASSESSMENTS AND ROLE OF ENVIRONMENTAL DRIVERS

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ABSTRACT. Soils of ice-free regions (oases) in East Antarctica have been rarely investigated via the prism of combined detailed biological and chemical methods. The main purpose of this work is to assess the influence of environmental factors, including microrelief and local features of the accumulation of biogenic material on the mineralization and humification of the organic matter in topsoils from Bunger Hills and Schirmacher Oasis. We used multiple techniques to analyze soil basal respiration and mineralization rates, extract humic acids, and investigate their molecular structure by ¹³C-NMR spectroscopy.

The results reveal that soil formed under moss cushions exhibits the highest levels of organic carbon (up to 2.43%), alongside elevated basal respiration rates, which reached up to 2.979±0.015 mg g⁻¹ day⁻¹ in moist conditions. Soil pH ranged from slightly acidic to alkaline, influenced by salt accumulation, which adversely affects plant communities and limits biomass production. Using ¹³C-NMR spectroscopy, although in a limited number of samples, we identified a predominance of aliphatic structures in humic acids with carboxylic functional groups, indicating significant vegetation influence on organic matter complexity. The sp²/sp³ carbon ratios (0.724 for Bunger Hills and 0.408 for Schirmacher Oasis) indicate a balance between potentially decomposable aliphatic and stable aromatic structures. Mineralization rates were significantly higher in soils with greater moisture retention, with cumulative CO₂ release reaching up to 150 mg CO₂/kg⁻¹ soil day⁻¹ over a 30-day period. Overall, our work revealed complex relationships between the environmental conditions and soil characteristics that significantly influence biological activity, carbon storage, and organic matter structure.

KEYWORDS: carbon sequestration, Antarctic, soil organic matter, humic acids, ¹³C-NMR

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INTRODUCTION

Ice-free areas in Antarctica, known as oases, nunataks, and dry valleys, cover approximately 55,000 km² and serve as critical sites for studying soil formation processes (Bockheim et al. 2008; Convey et al. 2014). Despite its remoteness and harsh climate, Antarctic soils are vital for understanding broader ecological dynamics and the impacts of climate change (Hodgson et al. 2014). Historically, Antarctic soils have been underinvestigated compared to other global regions. Pioneering studies by Ugolini et al. (1982) and Tedrow and Ugolini (1966) laid the groundwork for our understanding of these unique ecosystems. More recent investigations by Michel et al. (2014), Bockheim et al. (2015), Mergelov et al. (2015), and Lupachev et al. (2020) have further illuminated the diversity

and complexity of Antarctic soils. However, significant gaps remain in our knowledge, particularly regarding the intricate relationships between soil composition, microbial communities, and environmental factors (Cary et al. 2010; Elberling et al. 2013). Due to their geographically unique positions, the lowland Schirmacher Oasis and Bunger Hills are located along the coast in the ablation zone. The land areas and internal marine bays (epishelf water bodies) that make up these oases are separated from the open ocean by shelf glaciers that can be tens to hundreds of kilometers wide, and are bounded on the opposite side by outlet glaciers or the continental ice sheet. Due to the properties of the underlying surfaces in the oases (soil, rocks, water bodies), air temperatures throughout the year are on average 1-2 °C higher than the surrounding snow and ice areas; soil surfaces in the oases can warm to +41 °C, while

water surfaces can reach +17 °C (Gore and Leishman 2020). The oases also exhibit much more extreme temperature values than the surrounding glaciers (Kruchinin and Simonov 1967; Rusin 1958; Rusin 1961; Simonov 1971). The high frequency of strong winds (up to hurricane strength), low humidity, and limited precipitation (less than 200 mm per year) combined with high evaporation rates (over 500 mm) are also distinctive features of these lowland shelf oases.

In environments characterized by minimal decomposition and humification of organic residues, coupled with a limited duration of biological activity, soil formation processes are inherently slow. East Antarctic oases are characterized by the complete absence of typical soil-forming agents and humus sources such as vascular plants. Instead, these regions are dominated by mosses, lichens, and cyanobacteria, which create specialized microhabitats that support the development of unique microbial communities. Within these extreme conditions, soil microorganisms assume a central role in soil genesis, owing to their remarkable adaptations that enable survival and function under harsh environmental stresses (Nikitin et al. 2017; Savaglia et al. 2024). Microbial assemblages are fundamental to the functioning of Antarctic soil ecosystems. They are responsible not only for the decomposition of organic matter but also for facilitating nutrient cycling and contributing to the formation and stabilization of soil structure (Cary et al. 2010; Elberling et al. 2013). Recent investigations have emphasized the critical importance of understanding microbial community dynamics in relation to climate change, particularly concerning permafrost thawing and the consequent release of greenhouse gases (Schuur et al. 2015; Turetsky et al. 2020). The sensitivity of microbial activity to temperature variations is especially noteworthy; studies have demonstrated that microbial metabolic rates tend to increase with rising temperatures. Nonetheless, this response varies significantly among different microbial taxa and communities (Rinnan et al. 2009). Microorganisms adapted to cold environments generally exhibit lower temperature sensitivity compared to those from warmer regions (Nikitin et al. 2017). This differential responsiveness underscores the potential vulnerability of Antarctic microbial ecosystems as global temperatures continue to rise.

To better understand the effects of permafrost degradation and the potential release of greenhouse gases, precise knowledge of the spatial distribution of soil organic matter is needed, both in terms of quantity and quality (e.g. biodegradation, chemical composition, and degree of humification). Different authors used various indicators to identify the rate of humification in polar soils and the stability of the process, including the level of aromaticity. The rate of humification in soils can be inferred from ¹³C-NMR by observing changes in the relative proportions of different carbon structures, as more decomposed humic substances, indicating higher humification, typically show increased aromaticity and decreasing alkyl and O-alkyl carbon content. Therefore, a higher proportion of aromatic carbon and a lower proportion of alkyl and O-alkyl carbon in ¹³C-NMR spectra of soil organic matter suggest a higher rate and degree of humification (Vasilevich et al. 2018; Knicker 2006). The structural and molecular composition of soil organic matter in Antarctica has been studied previously by ¹³C-NMR spectroscopy (Alekseev and Abakumov 2024; Beyer et al. 1997, Abakumov and Alekseev 2018).

The assessment of carbon dioxide (CO₂) emissions in laboratory settings provides researchers with the ability to control various environmental factors that influence

these emissions, such as temperature (Carvalho et al. 2010). However, it is important to acknowledge that this approach has inherent limitations, including potential inaccuracies and significant time requirements. Laboratory conditions frequently alter the natural soil structure, significantly impacting microbial processes (Oertel et al. 2016). Typically, laboratory assessments focus primarily on respiration associated with the mineralization of soil organic matter (Carvalho et al. 2010; Oertel et al. 2016; Thomazini et al. 2016). Consequently, findings derived from laboratory studies cannot be directly correlated with *in situ* measurements, despite occasional similarities in observed trends. In contrast, *in situ* investigations encompass both autotrophic and heterotrophic (microbial) components contributing to ecosystem respiration (Oertel et al. 2016; Thomazini et al. 2016). Therefore, while laboratory experiments enable researchers to effectively evaluate the temperature sensitivity of soil organic matter mineralization under warming scenarios, they also facilitate estimates of CO₂ production potentials (Pires et al. 2017).

In the context of East Antarctica, it is evident that soil biological activity is generally low and heavily influenced by microclimatic conditions. Factors such as soil temperature and moisture levels critically affect primary productivity and carbon sequestration (Thomazini et al. 2016). The primary sources of soil organic carbon in ice-free regions predominantly include plants – such as mosses, lichens, and algae – as well as marine animals and birds (Michel et al. 2006; Zhu et al. 2014). Furthermore, bacterial mats occur in areas where shallow ponds previously existed, resulting in accumulations of minimally decomposed cyanobacteria that contribute insignificantly to terrestrial organic carbon reservoirs. Notably, the organic contributions from algae and lichens are substantially lower than those from bryophytes, which serve as the principal source of organic material in this region (Claridge et al. 2000). Additionally, carbon pools associated with Antarctic ice sheets or snow are rare due to the near absence of organic life forms (Claridge et al. 2000). Nonetheless, a minor influx of microbial organic material can enhance carbon storage capabilities within these soils (Claridge et al. 2000). Plants play a crucial role in facilitating carbon uptake through photosynthesis, while birds contribute locally through significant guano deposits (Michel et al. 2006; Thomazini et al. 2016). Moreover, substantial inputs of organic matter—particularly from guano—are recognized as critical processes driving soil formation and increasing organic carbon stocks within these ecosystems (Simas et al. 2007). The immobilization of carbon within soils through active incorporation by biomass and microorganisms not only fosters carbon sequestration but also enhances water retention capacity while influencing nutrient bioavailability and heavy metal dynamics (Schaefer et al. 2008; Thomazini et al. 2016).

Field studies combined with controlled laboratory experiments are commonly used to assess losses associated with organic carbon emissions (Oertel et al. 2016; Thomazini et al. 2016). In particular, potential mineralization losses from soils can be effectively evaluated through meticulously controlled laboratory settings. These methodologies are essential for analyzing the apparent stability of soil organic matter alongside its mineralization losses while predicting potential stability and losses within polar environments. However, it is crucial to recognize that data obtained from controlled laboratory experiments cannot be directly compared with those derived from field studies – such as those utilizing closed chamber methodologies. Nevertheless, data collected under standardized conditions

can provide valuable insights for subsequent simulation modeling regarding SOM transformation. Such studies are essential for evaluating the stability of organic matter and the potential for mineralization processes. It is important to emphasize that results from these laboratory experiments cannot be directly equated with those obtained from field studies, including methods like the closed chamber approach (Anderson 1982). However, the findings outlined in this section were derived from consistent laboratory conditions, which may enable their use in future modeling efforts related to the transformation of soil organic matter (Schmidt et al. 2011).

Previous research revealed that increased temperature sensitivity of microbial communities is linked with elevated mean annual soil temperature, thus proving the idea that microbial communities from colder regions are less temperature sensitive compared to warmer analogues (Rinnan et al. 2009).

Considering the relatively little attention given to the investigation of mineralization and microbial communities in soils of East Antarctica (especially in remote inner shelf oasis), our research is contributing crucial data on laboratory assessment of soil respiration rates and stabilization of organic matter in various soil types of rarely investigated areas of Bunger Hills and Schirmacher Oasis. In turn, this data is important for modelling of greenhouse gas emissions, carbon turnover, and soil organic matter stability under changing environmental conditions of Antarctica. The following objectives were chosen:

- Detailed studying of physical-chemical parameters of soils investigated across landscapes of ice-free areas of Bunger Hills and Schirmacher Oasis;
- Investigate the molecular composition of humic acids isolated from various soil types investigated in Bunger Hills and Schirmacher Oasis using ^{13}C -NMR spectroscopy.
- Assess the soil organic matter mineralization rates in

various soil types of Bunger Hills and Schirmacher Oasis using a laboratory incubation experiment.

MATERIALS AND METHODS

Soil samples for this study have been collected during the fieldwork of the 69th Russian Antarctic Expedition (February–March 2024) in two ice-free areas of East Antarctica – Bunger Hills and Schirmacher Oasis (Fig. 1). The main climatic parameters of the studied areas are provided in Table 1. In the field, soils were sampled from 20×20 cm soil pits from different depths. The samples were stored in double sterile plastic bags, labeled, and transported to the laboratory (Arctic and Antarctic Research Institute, Saint Petersburg, Russia).

Regional setting

Bunger Hills

Bunger Hills region is characterized by a complex geomorphological landscape comprising numerous islands and inlets situated on the inner continental shelf, overlain by morainic deposits. Geologically, the area is predominantly composed of metamorphic and igneous rocks, including gneiss, granite, and migmatite, reflecting its intricate tectonic history (Gore and Leishman 2020). A distinctive feature of this region is the pervasive presence of surface salts originating from marine aerosols, notably halite (NaCl) and thenardite (Na_2SO_4), which are observed on both lithic and soil surfaces (Gore and Leishman 2020). These salts are mobilized and redistributed during the austral summer months through aeolian processes; salt-laden aerosols are transported west-northwestward by prevailing winds emanating from adjacent marine inlets

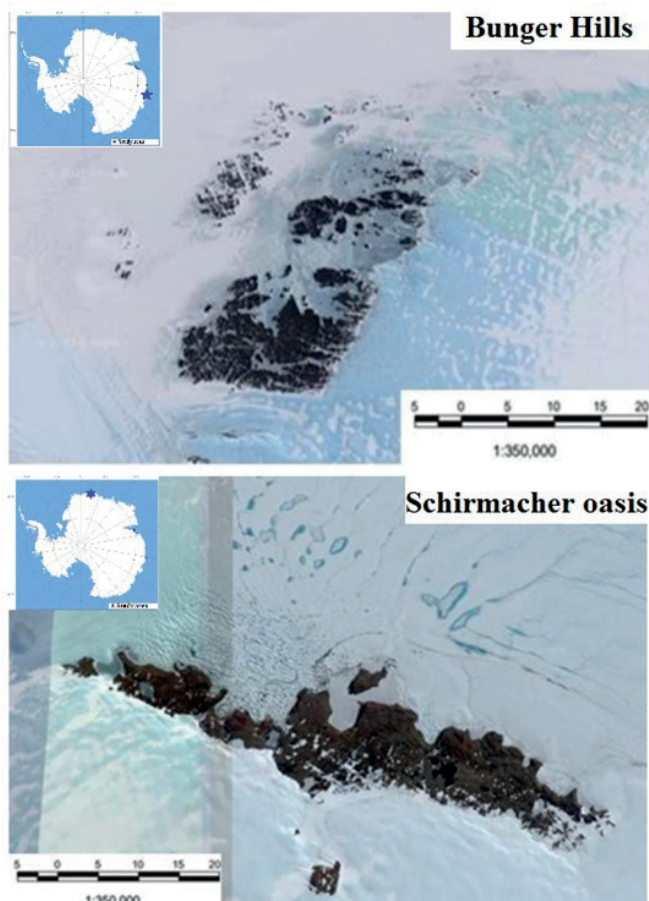


Fig. 1. Location and maps of Bunger Hills and Schirmacher Oasis

and hypersaline lakes. Wind-driven salt deposition results in the accumulation of evaporitic minerals on terrestrial surfaces located downwind of saline sources. Biotic colonization within the Bunger Hills is limited due to extreme environmental conditions; nonetheless, biological communities are represented primarily by lichens and mosses. The character of mosses' and lichens' distribution in Bunger Hills depends mostly on environmental conditions, particularly soil salinity and the availability of habitat and water (Leishman et al. 2020). Lichens are mostly represented by *Buellia frigida*, *Umbilicaria decussata*, *U. aprina*, *Xanthoria candelaria*, *X. elegans*, *Physcia caesia*, *Candelariella antarctica*, *Pseudophebe minuscula*, *Pertusaria globulifera*, *Buellia ligioides*, *Lecidea lapicida*, *Rhizoplaca melanophthalma*, *Lecanora expectans*, *L. polytropha*, *Rhizocarpon flavum*, *Rinodina petermannii*, *Usnea acromelaena*, *U. antarctica*, *Acarospora gwynnii*, and *A. Petalina* (Andreev, 1990). Mosses often described growing on soils and are represented by *Bryum algens Card.*, *Bryum argenteum Hedw.*, *Ceratodon purpureus (Hedw.) Brid.*, *Schistidium antarcticum (Card.) Sav.-Lyub. et Z. Smirn.*

These organisms are predominantly confined to meltwater channels – often associated with periglacial cracking phenomena – and to south-facing rock slopes in proximity to the Apfel Glacier (Leishman et al. 2020). These microhabitats provide critical refugia for extremophile communities adapted to survive under harsh polar conditions. The region also hosts a substantial lacustrine system, including Algae Lake, which ranks among the largest freshwater lakes in Antarctica and holds ecological significance for regional hydrology and biogeochemical cycles (Klokov and Verkulich 1994). Furthermore, the area supports an extensive terrestrial drainage network, recognized as the third-longest in Antarctica, facilitating surface runoff and subsurface flow pathways that influence landscape evolution and sediment transport processes (Gibson et al. 2002). The lichenometric method, based on the size of *Buellia frigida*, delineated that deglaciation was occurring from the center of the oasis in all directions towards its modern edges (Bolshiyarov and Verkulich 1992).

Schirmacher Oasis

The Schirmacher Oasis is an ice-free area on the border between the mainland and the ice shelf. The oasis is about 17 km long; it is stretched as a narrow three-kilometer strip in the direction from west-northwest to east-southeast. The oasis is separated from the Lazarev Sea (80 km), to the north by the Nivlisen ice shelf. On the south side, the oasis is bordered by the continental ice sheet, with the Wohlthat mountain range located on it (100 km). The most intense cyclonic winds from the east and southeast are dominant, which is accompanied by significant clouds, blizzards, snowfalls, and gale-force winds. Katabatic winds often blow, and the wind from the southeast direction causes a sharp decline in air temperature and wind speed, combined with

clear weather and a decrease in air humidity. The oasis is composed mainly of Precambrian age strata consisting of gneisses and crystalline schists. The oasis is characterized by a rather weak development of cellular forms of weathering and desquamation tiles on rock surfaces, as well as fairly recent traces of glacial impact, which indicates a relatively recent deglaciation, according to various estimates from 7 to 10 thousand years ago (Verkulich 2007). The vegetation of the oasis is exceptionally poor and is represented by some rare patches of lichens and mosses on rock substrates and fine earth. This decline is due to the harsh thermal regime, acute lack of liquid precipitation, low humidity, and frequent and strong winds, which create extremely unfavorable conditions for plant development (Kurbatova and Ochyra 2012; Singh et al. 2008). The frequency of species occurrence and changes in species composition varied across different locations. The lichen species growing on soil-moraine and moss habitats in Schirmacher Oasis include *Acarospora williamsii Filson*, *Buellia grimmiae Filson*, *Caloplaca citrina (Hoffm.) Th. Fr.*, *Candelariella flava (C. W. Dodge & Baker) Castello & Nimis*, *Lepraria cacuminum (A. Massal.) Lohtander*, *Lecanora expectans Darb.*, *Lecanora geophila (Th. Fr.) Poelt*, *Lecidella sipleyi (CW Dodge & GE Baker) May. Inoue*, *Lecidella sp. B*, *Physcia caesia (Hoffm.) Furnr.*, *Rinodina olivaceobrunea CW Dodge & GE Baker*. Mosses are most abundant along soil habitats near water bodies and meltwater streams and include *Bryum argenteum Hedw. var. muticum Brid.*, *Bryum archangelicum Bruch & Schimp*, *Bryum pseudotriquetrum (Hedw.) P. Gaertn., B. Mey. & Scherb*, *Ceratodon purpureus (Hedw.) Brid.*, *Orthogrimmia sessitana (De Not.) Ochyra & Zarnowiec*, *Syntrichia sarconeurum Ochyra & RH Zander*. Recent observations by ornithologists showed only Snow Petrels (*Pagodroma nivea*) and Wilson's Storm Petrels (*Oceanites oceanicus*) were reported breeding in the past (no current observation) with only South Polar skua (*Stercorarius maccormicki*) confirmed breeding in recent years (Ryan 2024). And, despite ornithogenic effect in Schirmacher Oasis being believed to be minor, new data obtained during current fieldwork revealed the appearance of breeding colony of Adelie penguins *Pygoscelis adeliae* (20 breeding pairs were found in December 2024–January 2025) (Galustov et al. 2025).

Laboratory analyses and procedures

The soil samples were air-dried at room temperature and subsequently passed through a 2 mm plastic sieve prior to chemical analysis. To determine the pH, a pH meter was used (pH-150 M), utilizing a soil-to-solution ratio of 1:2.5. The soil organic carbon, nitrogen, and hydrogen content was quantified using a Vario EL III analyzer (Elementar, Germany). For the assessment of particle size distribution, the pipette-sedimentation method described by Kachinsky (1958) was used.

Soil mineralization rates were obtained through a controlled laboratory incubation experiment, which was conducted in five replicates for each soil horizon. The CO₂

Table 1. Climatic parameters of the study areas (data from ROSHYDROMET, <http://www.wmo.int/pages/prog/www/Antarctica>)

MAAT, °C	MAST, °C	MAGT, °C	Mean annual wind speed, m s ⁻¹	Annual precipitation, mm (in liquid equivalent)
Bunger Hills				
-9	-8,8	-7,8	6,8	204
Schirmacher Oasis				
-10,5	-10,0	-10,0	9,7	264,5

respiration rate emissions were measured following the methodology outlined by Anderson (1982). Specifically, plastic cylinders with dimensions of 10 cm in diameter and 20 cm in height were employed for this purpose. During the controlled laboratory incubation, 10 g of mineral soil and 5 g of organic material were placed within the cylinders. Subsequently, these cylinders containing soil samples – maintaining a moisture content of approximately 60% of their water holding capacity – were positioned in beakers filled with water at the bottom to simulate field conditions typical of paddy environments. Throughout the incubation period, the water content (%) was monitored to ensure consistency.

Following this initial phase, aliquots of the soil samples were transferred to sealed plastic bottles containing 1 M NaOH and maintained at a temperature of 20°C. The amount of CO₂ trapped by the alkaline solution was quantified through titration after a period of 7 days of incubation. The overall incubation duration lasted for 112 days, during which duplicate measurements were conducted for 10% of the samples to ensure reliability.

We followed the standard methods set out by the International Humic Substances Society (IHSS 1981) to get humic acids (HAs) from topsoil horizons. We used Swift (1996) to get humic substances and the residue. Initially, HAs from the studied soils were air-dried before recording their ¹³C-NMR spectra using a JNM-ECA 400 NMR spectrometer (JEOL, Tokyo, Japan). This analysis employed the Cross-Polarization Magic Angle Spinning procedure at a spinning speed of 6 kHz with a contact time of 5 ms and a recycle delay of 5 s. Adamantane (29.46 ppm) served as the reference material for chemical shifts. Data corrections were applied for water and ash content; additionally, oxygen content was calculated based on the difference between sample mass and gravimetric concentrations of carbon (C), nitrogen (N), hydrogen (H), and ash. Leonardite HA standard (1S104H) and Elliot soil HA standard (1S102H) were utilized as reference materials during this analysis. The acquired ¹³C-NMR spectra underwent transformation into quantitative forms using Fourier transformation techniques. Fragment matching was performed according to literature data (Kechaykina et al. 2011; Chefetz et al. 2002), based on specific chemical shift ranges as detailed in Table 2. Data processing was conducted using MestreNova software (Mestrelab Research S.L., Spain).

The sp²/sp³ carbon ratio was calculated according to Eq. (1) (Mao et al. 2000):

$$sp^2/sp^3 = (\text{area (108–220 ppm)})/(\text{area (0–108 ppm)}) \quad (1)$$

where sp² is sp² hybridized carbons; sp³ is sp³ hybridized carbons.

RESULTS

Soil morphology

Both in Bunger Hills and Schirmacher Oasis, an extensive part of the ice-free area is occupied by inter-ridge valleys (Fig.2), where cryoturbated soils with high gravel content (less often sandy) predominate – more often Leptosols are identified (Table 2). These soils are formed in the complete absence of higher plants, so organogenic horizons are formed mainly of microbial and cryptogamic autotrophs. In some cases, organogenic horizons are not formed at all, leading to negligible TOC content (Mergelov et al. 2018). These soils are especially widespread in parts of the oases where surface accumulation of soluble salts is observed. Wind erosion is actively involved in the formation of this type of soil, which contributes to the corrosion of upper horizons (Tedrow and Ugolini 1966). In addition, most of the landscapes are occupied by bedrock and aggregations of coarse-grained material, on which only epilithic and endolithic soil-like bodies are developed, which were previously described (Mergelov et al. 2018; Friedmann et al. 1982).

In inter-ridge valleys, where Leptosols are mainly found, the main factor determining the development of biotic complexes on the soil surface is the diversity of micro- and mesorelief forms - wind shelters can exist on the sides of valleys and in rock cavities, which contributes to the formation of perennial snowfields and the redistribution of moisture (Dolgikh et al. 2015; Zazovskaya et al. 2017). Therefore, differences in the thickness and composition of organogenic horizons are determined primarily by the distribution of melting waters over meso- and microrelief (Fig. 3). These can be surface algobacterial complexes of subaqueous soils developing along the shores of lakes with a pulsating water regime, surface or subaerial horizons dominated by mosses, or hidden under gravel pavements - hypolythic algobacterial horizons. At the same time, an interesting feature of amphibian soils under algal-bacterial mats is the development of a saline-type profile (dark gray horizons of sulfide salinity, glaucous peeled and ferruginous-metamorphic horizons).

Table 2. Structural composition of HAs based on chemical shifts on ¹³C-NMR spectra (Kogel-Knabner 1997)

Chemical Shift (ppm)	Type of Structural Fragment
0-10	Methyl (–CH ₃) and methylene (–CH ₂) groups
10-27	H- and C-substituted aliphatic fragments
27-50	CH ₂ -alkyl structures
50-70	Methoxyl (–OCH ₃) fragments, amino acid groups, and ether groups
70-100	O- and N-substituted aliphatic fragments
100-108	Anomeric carbon in sugars
108-135	Protonated aromatic carbon
135-150	Alkylaromatic groups
150-170	Aromatic carbon of phenols and esters
170-190	Carboxyl (–COOH) and carbonyl (C=O) groups
190-220	Carbonyls in conjugated systems

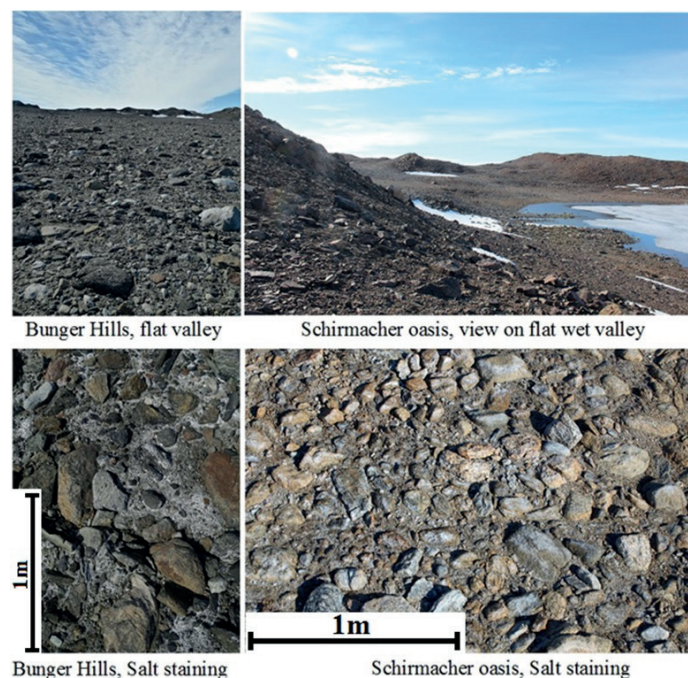
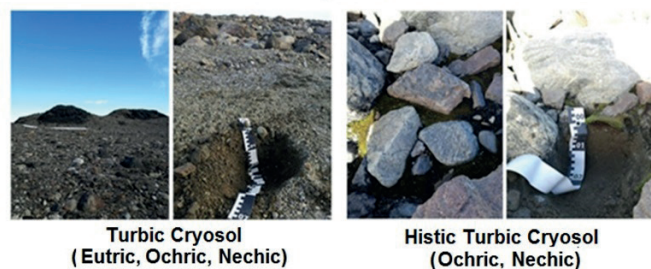


Fig. 2. Typical flat valleys and salt staining manifestations in Bunger Hills and Schirmacher Oasis, East Antarctica

Bunger Hills



Schirmacher Oasis

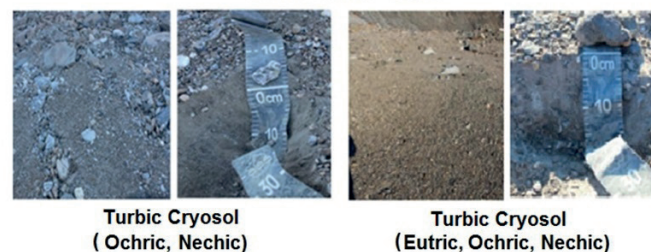


Fig. 3. Studied soil profiles and respective landscapes of Bunger Hills: slope of a valley composed of boulder debris in a sandy matrix (left), wind shelter near the melting snow patch (right); Schirmacher Oasis – patterned ground in the dry valley (left); dry flank of a valley with gravel pavement and salt staining (right)

In Bunger Hills, due to the formation of large flat surfaces of inter-ridge valleys as well as strong katabatic winds, fresh snow is actively blown out (Gore and Leishman 2020). In addition, moraines with high gravel content are very widespread, which leads to greater moisture deficit in the upper soil horizons as well as smaller spatial coverage of organogenic soils compared to other ice-free areas of Antarctica (even compared to East Antarctica oases). Another characteristic feature of Bunger Hills is very limited ornithogenic transfer, which is due to the absence of penguin rookeries and very rare nesting of flying birds. In addition, carbonate-chloride-sulfate and carbonate salts on the surface are extensively represented in the oasis, which also complicates the development of soils (Gore and Leishman 2020). Soils with the most developed vertical profiles are formed in wind shelters and locally in places of ephemeral melting of snow patches with thicker moss-lichen cushions (Fig. 4). However, this soil variety occupies less than 0.1% of the area. An interesting feature

of the area is the predominance of loamy parent material, which determines a weak development of hypolythic organogenic horizons together with the occurrence of cryometamorphic soils (characterized by a specific granular structure in the sub-surface horizon).

Soil physico-chemical characteristics

Schirmacher Oasis

The highest levels of organic carbon and nitrogen accumulation, along with the greatest rates of basal respiration, were observed in Histic Turbic Cryosol that develops beneath a moss cushion approximately 3 cm thick, in a micro-depression where water likely accumulates from melting snowfields during the summer months (Table 3). It is important to note that such conditions are atypical for the harsh climatic environment characteristic of this offshore oasis.



Fig. 4. Moss cushions in Bunger Hills (wind shelter in south-western part) and in Schirmacher Oasis (wet valley in south-eastern part)

Table 3. Soil physico-chemical characteristics in Bunger Hills and Schirmacher Oasis

Soil ID and name	Soil depth, cm	pH _{H₂O}	pHKCl	TOC, %	N, %	H, %	C:N	Basal respiration, mg g ⁻¹ day ⁻¹	Fine earth (<2 mm), %
Bunger Hills									
Bunger 1 Turbic Cryosol	0-2	8.12 ± 0.32	–	0.77 ± 0.10	0.073 ± 0.005	0.21 ± 0.04	10.45 ± 1.27	0.009 ± 0.001	18.69 ± 1.13
Bunger 1 Turbic Cryosol	2-20	7.56 ± 0.21	–	0.86 ± 0.16	0.062 ± 0.005	0.12 ± 0.02	12.26 ± 2.09	0.012 ± 0.001	21.71 ± 1.87
Bunger 2 (wind shelter, moss) Histic Turbic Cryosol	0=1	5.32 ± 0.19	4.87±0.12	3.43 ± 0.43	0.270 ± 0.090	0.49 ± 0.10	14.30 ± 1.23	0.095 ± 0.010	25.71 ± 2.87
Bunger 2 (BC) Histic Turbic Cryosol	1-23	5.76 ± 0.23	5.34 ± 0.12	0.75 ± 0.11	0.071 ± 0.005	0.15 ± 0.03	10.32 ± 1.57	0.009 ± 0.001	21.49 ± 1.14
Bunger 3 (salt staining) Turbic Cryosol	0-1	8.87 ± 0.23	–	0.70 ± 0.14	0.068 ± 0.005	0.17 ± 0.06	11.08 ± 2.12	0.007 ± 0.001	21.11 ± 1.47
Bunger 3 Turbic Cryosol	1-16	7.42 ± 0.11	–	0.70 ± 0.12	0.065 ± 0.005	0.12 ± 0.02	10.56 ± 1.37	0.006 ± 0.001	23.71 ± 1.87
Bunger 6 (moss) Histic Turbic Cryosol	0-2	5.12 ± 0.15	–	2.43 ± 0.23	0.210 ± 0.090	0.31 ± 0.10	11.30 ± 1.23	0.050 ± 0.009	32.71 ± 1.07
Bunger 6 (BC) Histic Turbic Cryosol	2-21	6.12 ± 0.23	–	0.89 ± 0.09	0.091 ± 0.005	0.12 ± 0.03	8.32 ± 1.09	0.021 ± 0.001	22.71 ± 2.17
Schirmacher Oasis									
Novo-3 (moss) Histic Turbic Cryosol	0-3	6.09 ± 0.12	5.87 ± 0.14	2.43 ± 0.12	0.170 ± 0.080	0.49 ± 0.98	14.30 ± 0.51	2.979 ± 0.015	28.71 ± 1.67
Novo-3 (BC) Histic Turbic Cryosol	3-6	5.66 ± 0.15	5.12 ± 0.15	0.50 ± 0.07	0.075 ± 0.010	0.17 ± 0.03	6.63 ± 0.10	0.149 ± 0.010	23.22 ± 1.62
Novo-7 (moss) Histic Turbic Cryosol	0-2	7.70 ± 0.15	–	0.06 ± 0.01	0.019 ± 0.007	0.14 ± 0.02	2.73 ± 0.05	0.195 ± 0.010	31.71 ± 1.85
Novo-7 (BC) Histic Turbic Cryosol	2-8	6.25 ± 0.16	5.96 ± 0.10	0.05 ± 0.01	0.023 ± 0.005	0.16 ± 0.03	2.30 ± 0.12	0.138 ± 0.010	24.22 ± 1.12

*values show mean ± standard deviation

In both the Schirmacher Oasis and the Bunger Hills, instances of surface salt accumulation have been frequently documented, which adversely impacts the development of plant communities, particularly mosses and lichens. Consequently, the spatial extent of areas exhibiting increased biomass production is extremely limited within the studied region of the Schirmacher Oasis. The pH levels of the examined soils range from slightly acidic to acidic in horizons located beneath moss cushions within wind shelters, transitioning to alkaline conditions in areas with active salt accumulation. Elevated soil respiration rates typically corresponded with increased concentrations of organic carbon and nitrogen, as well as a modest rise in fine earth content. The density of the solid phase of the soils increases from surface horizons – where minimum density is characteristic for peaty layers—to central horizons, a trend associated with varying degrees of fine earth presence and its weathering processes. Areas subjected to anthropogenic influence exhibit higher bulk density values.

Bunger Hills

Soil pH in the Bunger Hills exhibits variability, ranging from slightly acidic to acidic in horizons located beneath moss cushions within wind shelters, while alkaline conditions are observed in areas characterized by active salt accumulation. Salt accumulation is influenced by the active weathering of massive crystalline and friable rock formations. Research indicates that the oasis is delineated by a “salt line”, which partitions it into two distinct regions, thereby influencing the intensity of rock weathering as well as the distribution and growth of salt-sensitive flora, including mosses and lichens (Gore and Leishman 2020).

Total carbon content within these soils varies considerably, with values ranging from 0.70% to 2.43%. Soils located in wet valleys and wind shelters that support developed moss covers exhibit higher carbon concentrations compared to other soil-like bodies. A notable characteristic of the Bunger Hills is the creation of conditions conducive to a significant deficit of liquid moisture during summer months, even in the upper soil

horizons. Consequently, the extent of moistened areas – primarily resulting from snowmelt or ephemeral stream flows – is minimal relative to other previously studied ice-free regions. This phenomenon is attributed to the widespread presence of moraines with high gravel content in valleys and troughs.

Soil basal respirometry

The oases of East Antarctica are generally characterized by much more severe climatic conditions (a short period of biological activity, harmful ultraviolet radiation for macroscopic life forms, strong winds, large temperature fluctuations), as well as a more homogeneous composition of organic residues with a simultaneous decrease in the total organic carbon content. On average, soil carbon dioxide emissions on King George Island and Ardley Island are 0.076–0.122 mg g⁻¹ day⁻¹, which is higher than the average values described for the oases of East Antarctica (Fig. 5). The highest rates of soil respiration were described for soils developing under *Deschampsia Antarctica* – up to 0.210 mg g⁻¹ day⁻¹, which was described earlier (Abakumov and Mukhametova 2014; Thomazini et al. 2016).

Our results showed that the soils of wet valleys, as well as the soils of wind shelters, are the most important participants in the biogeochemical carbon cycle in the coastal and offshore oases of East Antarctica (especially in the almost absence of direct and indirect ornithogenic input of organic matter, which is observed in Bunger Hills). Soil respiration in the oases of East Antarctica is characterized by the absence of root respiration, as there are no representatives of higher vegetation. Thus, soil respiration is mainly characterized by the dominance of microbial respiration (both heterotrophic and autotrophic). In the case of the development of moss cushions in conditions of wind shelters and moist valleys, respiration due to moss rhizoids is also observed in the soils. Generally, in the studied oases, soil respiration rates have been found with the highest values of basal respiration being typical for soils of wind shelters (up to 0.125 mg g⁻¹ day⁻¹) (Table 3). CO₂ emissions are lower in the surface horizons of soils in moist valleys with less dense moss cover (0.068–0.098 mg g⁻¹ day⁻¹). “Amphibian soils” developing on the shores of lakes with a pulsating water regime and

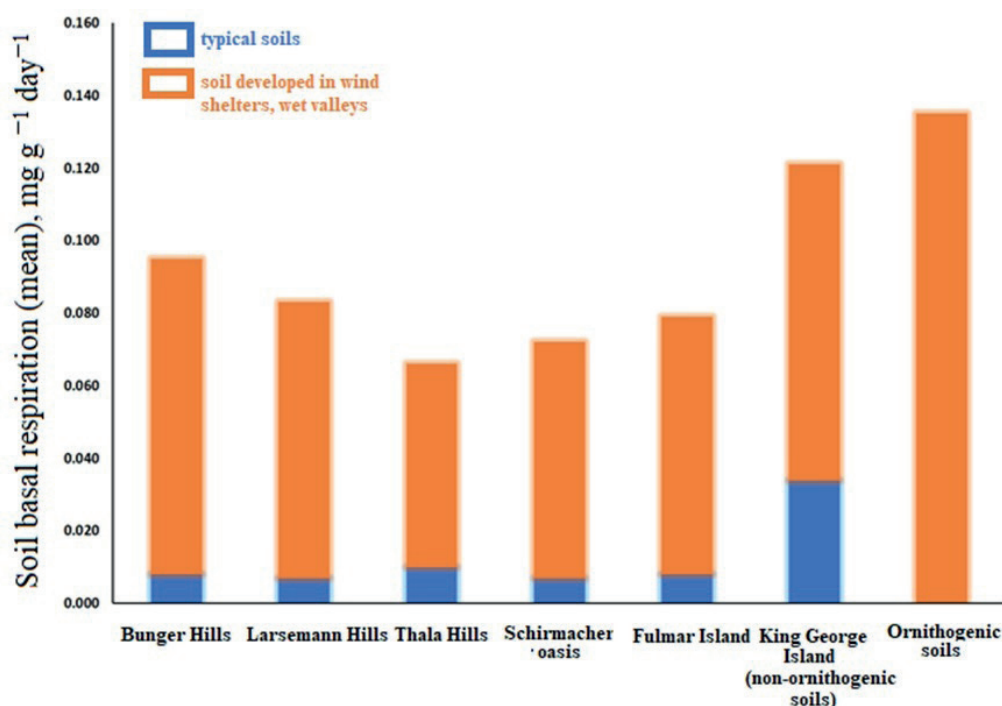


Fig. 5. Soil basal respiration rates in different ice-free areas of East and Maritime Antarctica (own data, unpublished)

surface algobacterial mats are characterized by carbon dioxide emission levels of 0.042–0.102 mg g⁻¹ day⁻¹. Finally, the lowest CO₂ emissions are typical for “ahumic” soils without macroscopic organogenic horizons (0.005–0.010 mg g⁻¹ day⁻¹). Soil moisture from melting snowfields has a critical effect on carbon dioxide emission levels during periods of low liquid precipitation in the oases of East Antarctica. Previously, authors showed that a decrease in soil moisture from 40 to 10% leads to a reduction in carbon dioxide emissions by more than three times (Mergelov et al. 2015, Mergelov et al. 2018). At the same time, seasonal and interannual dynamics in CO₂ emission levels depend more on the level of moisture in a particular summer season than on the duration of exposure of vegetation without snow in summer (in days), when biological activity is suppressed in the case of a low level of meltwater intake from summer snowfalls.

Although soil respiration levels in wind-sheltered soils within East Antarctic oases are comparable to those observed in Maritime Antarctic soils – and align with previously reported levels in the Russian Arctic (Alekseev et al. 2022) – the spatial extent of such sites in East Antarctica is limited. Average soil CO₂ emissions in the studied oases of Bunger Hills and Schirmacher Oasis exceed those documented for the Dry Valleys (Archer et al. 2018), yet remain lower than emissions observed on King George Island and Ardley Island. According to Dennis et al. (2013), climate warming is expected to impact soil microbial communities differently in subantarctic versus coastal Antarctic environments. Studies examining latitudinal gradients in Antarctic soil biological parameters have demonstrated that microbial temperature sensitivity increases with higher mean annual soil temperatures. Consequently, bacterial communities in colder regions, such as East Antarctic oases, tend to be less responsive to temperature changes than those in warmer, more maritime regions of Antarctica (Rinnan et al. 2009).

These findings suggest a pronounced gradient in microbial activity from the coastal and inland oases of East Antarctica toward the less extreme environments of Maritime Antarctica. This gradient is influenced by variations in soil temperature regimes, enzymatic activity, and pools of organic carbon, nitrogen, and phosphorus. It is worth highlighting that there remains limited research focused on soil respiration and biological activity across the diverse eco-climatic regions of Antarctica. Earlier, Russian researchers (Lupachev et al. 2020) proposed potential ecological and climatic shifts that could influence soil formation in East Antarctic oases. They suggest that increases in mean annual air temperatures and changes in hydrological conditions – such as prolonged soil biological activity periods and enhanced moisture availability – may

lead to greater accumulation of organic matter. This, in turn, could promote the stabilization of surface cover by mosses and lichens and facilitate the prolonged preservation of organic material in situ.

Estimation of CO₂ emission rate and mineralization of organic matter in Antarctic soils

Cryogenic soils show negligible organic decomposition, driven by persistent low temperatures that severely restrict microbial mineralization, oxygen deficiency that inhibits oxidase activity, and complex substrates with very low nitrogen content that further hinder microbial metabolism (Freeman et al. 2001; Moore and Basiliko 2006).

Despite the fact that the number of studies on the assessment of carbon pools in cryogenic soils has increased over the past decades (Michel et al. 2014; Mergelov et al. 2015; Schaefer et al. 2008), the issues of quantifying soil carbon reserves and mineralization potential are still problematic and controversial. Despite the fact that the period of biological activity and positive temperatures in the oases of East Antarctica is short, there is still a certain variety of soil processes that are associated with the transformation of organic matter and the activity of biota. In particular, the question of the rate of mineralization and intensity in the case of different soils and different sources of humus formation in both Western and Eastern Antarctica was discussed earlier (Abakumov 2010). It can be said that mineralization and humification processes can occur in all Antarctic soils where organic matter is present. However, it is worth noting that, unlike most soils, the humification process in Antarctic soils is accompanied by the formation of an increased amount of fulvic acids with a low proportion of humic substances and the dominance of aliphatic structures, which will be shown below using the example of ¹³C-NMR spectra (Alekseev and Abakumov 2024). The rate of CO₂ emission from the surface horizons of the soils of East Antarctica oases was different (Table 4). The cumulative production of C-CO₂ by the surface horizons of soils in wind shelters and wet valleys averaged 282.97 mg of CO₂/kg⁻¹ soil day⁻¹, while soils developing without local mitigation of soil formation conditions – 69.92 CO₂/kg⁻¹ soil day⁻¹. As shown in Table 4, soil CO₂ emissions displayed two pronounced peaks: an initial one within the first 1–3 weeks, followed by a second, more substantial peak at 13–14 weeks. This dual-peak pattern is a universal trait observed across nearly all studied soils.

During soil incubation, the amount of C-CO₂ released reflects both microbial vitality and the organic matter's vulnerability to breakdown. The data show a rapid and continuous decline in CO₂ emissions, especially in the

Table 4. Average CO₂ emission rates, mg CO₂/kg⁻¹ soil day⁻¹

Soil ID and horizon depth, cm	1-3 week	4-7 week	8-11 week	12-15 week	16-19 week
Bunger 1 0–2 cm	163.2 ± 12.1	142.0 ± 7.2	123.2 ± 9.7	92.3 ± 7.6	81.2 ± 4.5
Bunger 1 2–20 cm	191.2 ± 10.5	161.2 ± 12.1	142.1 ± 8.8	92.3 ± 6.5	71.2 ± 5.4
Bunger 3 0–1 cm (salt staining)	221.2 ± 17.6	181.2 ± 14.1	152.1 ± 10.4	122.3 ± 9.2	101.2 ± 10.4
Bunger 3 1–16 cm	181.2 ± 6.1	161.2 ± 7.1	142.1 ± 10.5	94.3 ± 8.1	71.2 ± 8.2
Bunger 6 0–2 cm (moss)	753.1 ± 5.1	641.2 ± 12.4	574.2 ± 15.6	531.2 ± 20.1	421.2 ± 10.4
Bunger 6 2–21 cm (BC)	563.2 ± 5.7	454.2 ± 15.4	453.1 ± 12.3	374.0 ± 9.7	333.1 ± 12.4
Novo 7 0–2 cm	563.1 ± 10.4	452.1 ± 14.1	341.2 ± 13.1	191.1 ± 7.6	181.2 ± 12.7
Novo 3 0–3 cm (moss)	567.6 ± 12.4	364.2 ± 19.2	174.3 ± 8.7	202.1 ± 12.5	91.2 ± 8.5

surface organic layers, signaling a swift shift toward stabilization that makes organic matter highly resistant to decay from biological or environmental forces. In contrast, destabilization reverses this trend, stripping organic components of their resistance and making them easily accessible for microbial consumption (Six et al. 2006). Ornithogenic soils are characterized by organic matter stability, while in deeper mineral horizons, mineralization rates are lower – likely due to changes in humic acid composition, such as altered ratios of carboxyl groups and aliphatic structures driven by ornithogenic influence. These profound structural modifications play a decisive role in controlling decomposition rates, demonstrating that ornithogenic factors fundamentally reshape the organic matter system and promote its stabilization (Ejarque and Abakumov 2016).

¹³C-NMR spectroscopy of humic substances

The application of ¹³C-NMR spectroscopy in studying Antarctic Cryosols provides critical insights into carbon storage mechanisms, nutrient cycling processes, historical climate records, and potential feedback loops that could influence future climate scenarios. It is crucial to note that the limited amount of samples analyzed in this section primarily stems from the challenges encountered in obtaining sufficient quantities of humic acids from each soil sample, which is largely attributed to the low levels of organic matter present in soils of Leptosols in East Antarctica. Moreover, there is a significant deficiency of published studies addressing the molecular composition of soil organic matter (SOM) in East Antarctica. That is why it is a vital imperative to undertake extensive instrumental investigations in these remote offshore environments to deepen our understanding of organic matter composition and the mechanisms underlying its stabilization. We have analyzed two topsoil samples from Bunger Hills (Turbic Cryosol, Bunger 1 0–2 cm) and Schirmacher Oasis (Histic Turbic Cryosol, Novo 7 0–2 cm).

The findings regarding the elemental composition of the isolated humic acids (HAs) from the topsoil horizons are presented in Table 5. Notably, the low carbon content observed in HAs can be attributed to a predominance of aliphatic structures, with aromatic components being present only in trace amounts. This suggests that the HAs in this region are characterized by a higher proportion of non-aromatic carbon compounds. The C/N ratio, which ranges from 10.06 to 10.73 in the studied samples, further supports the notion of low carbon availability in peripheral compounds, coupled with a relatively high nitrogen content.

The ¹³C-NMR spectral shapes of humic acids extracted from investigated topsoil horizons are shown in Fig. 6. Both samples exhibit a predominance of aliphatic structures, which have been documented in previous studies (Beyer et al. 1997, Alekseev and Abakumov 2024; Zech et al. 1997).

A particularly notable feature observed in the ¹³C-NMR spectrum from the Turbic Cryosol in Bunger Hills is the presence of a prominent peak at a chemical shift of 173.89 ppm. This peak is characteristic of carbonyl carbons (C=O) associated with functional groups such as carboxylic acids, esters, and amides. The intensity and position of this peak suggest significant organic matter transformation processes influenced by the accumulation of moss-lichen vegetation, which contributes to the development of a more complex peripheral aliphatic component within humic acids. In addition to this key peak, several other significant chemical shifts were observed in the spectra. For instance, peaks around 30 ppm correspond to methylene carbon atoms (–CH₂–), which are often associated with lipid components within organic matter (Alekseev and Abakumov 2024; Keeler et al. 2006). The presence of these lipids indicates microbial activity and organic matter decomposition processes that are critical for nutrient cycling in these cold environments. The methylene carbon signals can also reflect the degree of saturation and structural complexity of lipids present, providing insights into microbial community composition and metabolic pathways.

In general, most of the peaks on the ¹³C-NMR spectra of Turbic Cryosol from Bunger Hills were in the region of alkyl-C (0–60 ppm). Previous research has established that the decomposition of soil organic matter is generally accompanied by a shift in carbon functional groups, notably an increase in alkyl carbon content and a concomitant decrease in O-alkyl carbon fractions (Shen et al. 2018). This transformation reflects the preferential breakdown of labile, easily degradable components such as polysaccharides, which are highly accessible to microbial enzymes. As microbial activity progresses, these labile compounds are rapidly mineralized, leading to a relative enrichment of more recalcitrant alkyl structures that are resistant to further decomposition. This pattern underscores the dynamic nature of organic matter turnover and the selective degradation of specific molecular pools during soil organic matter decomposition processes.

The most intense peak on a ¹³C-NMR spectra of HA isolated from Histic Turbic Cryosol from wind shelter in Schirmacher Oasis is found at 173.18 ppm. This is most likely due to carboxyl carbon on aromatic rings or in esterified fatty acids (Li et al. 2003; Preston and Schnitzer 1987). The peak at 30.39 ppm in the alkyl-C region is assigned as –CH₂–methylene carbons. At 22.73 ppm, a prominent peak of CH₃ was also observed, which could be due to the presence of aliphatic chains of various components such as lipids/waxes (Simpson et al. 2011). In soil from Schirmacher Oasis, another (less prominent) peak was observed at 71.77 ppm, which is attributed by some authors to quaternary C bonded to oxygen (O) (Nebbioso et al. 2015). However, as discussed by Gamage et al. (2024) the peak at 70 ppm could have originated from the modified and relatively hydrophobic carbohydrate structures. ¹³C-NMR spectra of humic acids from both Schirmacher Oasis and Bunger

Table 5. The elemental composition of humic acids from studied topsoil horizons

Soil ID	C, %	H, %	N, %	O, %	C/N	H/C	O/C	Ash, %
Turbic Cryosol, Bunger 1 0–2 cm	49.01	5.01	4.87	41.11	10.06	0.10	0.83	4.35
Histic Turbic Cryosol, Novo 7 0–2 cm	52.03	4.92	4.85	38.2	10.72	0.09	0.73	4.20
CV, %	4,23	1,28	0,29	5,19	0,80	7,44	9,07	2,48
Leonardite HA standard (1S104H)	63.81	3.7	1.23	31.27	51.88	0.006	0.49	2.6
Elliot soil HA standard (1S102H)	58.13	3.68	4.14	34.08	14.04	0.06	0.59	0.9

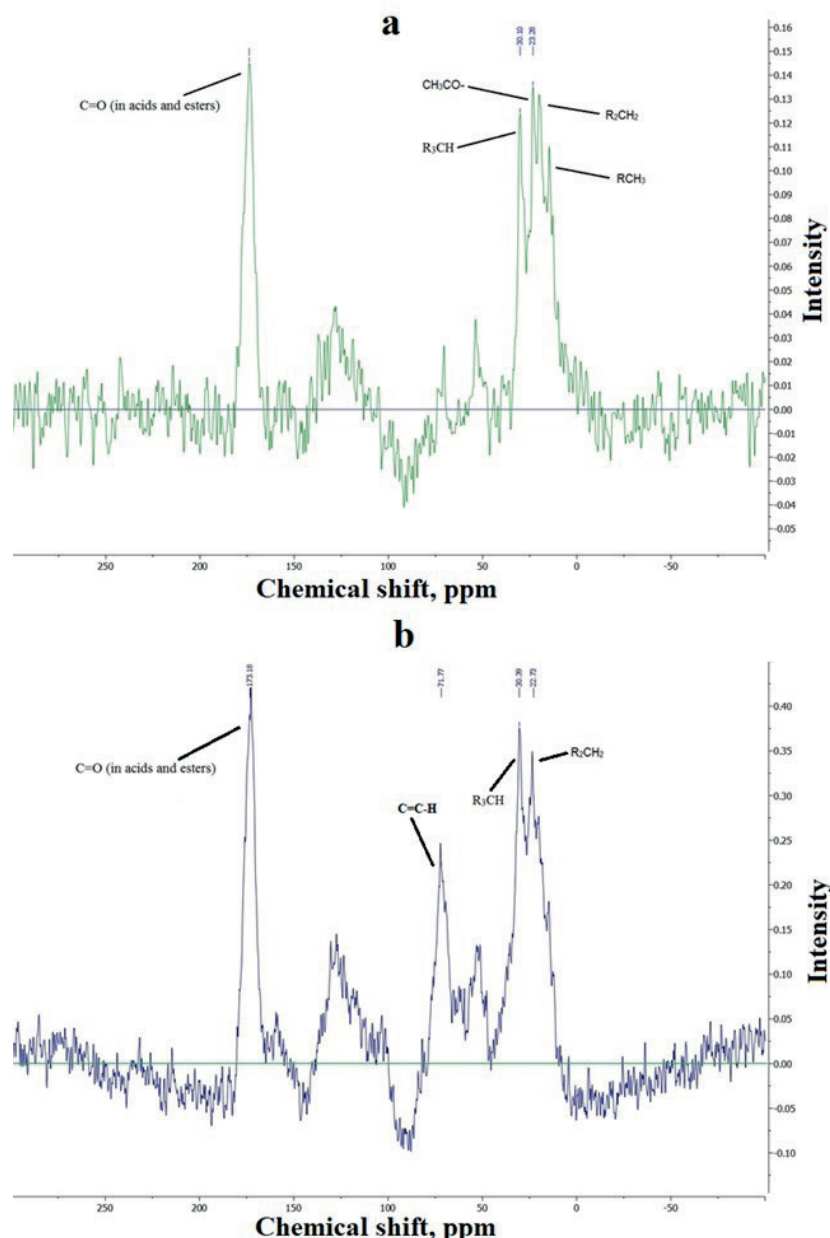


Fig. 6. ^{13}C -NMR spectra of Has isolated from studied topsoils in Bungler Hills (Bunger 2, 0–1 cm, a) and Schirmacher Oasis (Novo 7, 0–2 cm, b)

Hills showed quite low signs in the area of 110–140 ppm, which indicate weak contributions of phenol as it occurs in the lignin or aromatic amino acids group (Knicker et al. 2006).

Overall, the hydrophobic nature of aliphatic components described makes humic substances resistant to microbial degradation (Mylotte et al. 2016). Previous findings by Gamage et al. (2024) revealed that this can be explained by highly decomposed aliphatic/alicyclic molecules. At both ^{13}C -NMR spectra of humic acids, we have found significant contributions from non-protonated O-alkyl-C and non-polar alkyl protons, which could be attributed to their origin from the carboxyl-rich alicyclic CRAM structures (Cao et al. 2016; Garage et al. 2024). We can also prove this finding, since we also found a notable presence of carboxylic acid, indicated by a peak at 170 ppm characterizing CRAM-like structures (Hertkorn et al. 2016).

Analysis of both ^{13}C -NMR spectra from Bungler Hills revealed that SOM is more degraded (or humified) compared to that from Schirmacher Oasis, where some plant material (moss) inputs were detected. This is also supported by a lower contribution of O-alkyl carbon on a spectrum (a) and a reduced O-alkyl C/alkyl C ratio, which shows a

lesser extent of decomposition. The same were previously observed by Pradel et al. (2023). However, a higher intensity of peaks was noted in the carboxylic region between 220 and 160 ppm in the topsoil sample from Schirmacher Oasis. Our findings align with previous studies, confirming that aliphatic carbon predominates over aromatic carbon while exhibiting lower levels of carbonyl carbon.

Moreover, smaller peaks observed between 50–60 ppm can be attributed to carbon atoms involved in ether linkages or aliphatic carbon structures, suggesting contributions from plant-derived materials and microbial metabolites. These shifts reflect the structural diversity within soil organic matter and its dynamic interactions with soil minerals. The presence of ether linkages is particularly important, as they can enhance the stability and recalcitrance of organic matter against microbial degradation. Peaks in the range of 100–110 ppm may indicate aromatic carbon structures, which are typically resistant to decomposition and play a crucial role in long-term carbon storage within soil profiles. Aromatic compounds contribute to soil stability through their ability to form strong interactions with soil minerals, thereby influencing overall carbon dynamics and nutrient retention.

Almost no peaks were observed around 60–80 ppm, which usually represent carbons attached to hydroxyl groups (–OH) or those involved in hydrogen bonding within humic substances. These functional groups are essential for understanding how organic matter interacts with soil minerals and affects nutrient availability. Hydroxyl groups can also participate in complexation reactions with metal ions, further influencing nutrient cycling processes. The comprehensive analysis of these chemical shifts not only enhances our understanding of the biochemical composition and functional roles of organic matter in Antarctic Cryosols but also provides insights into how these ecosystems respond to environmental changes. By elucidating the structural characteristics and dynamics of soil organic matter through ^{13}C -NMR spectroscopy, we can better assess potential impacts on carbon cycling and storage under changing climatic conditions. Furthermore, specific attention should be given to interpreting minor peaks that may appear within the spectra. For example, signals between 0–10 ppm could indicate methyl (–CH₃) groups associated with microbial byproducts or fresh plant material inputs. These low-field signals can provide valuable information regarding recent biological activity and organic matter turnover rates.

The ratio of sp^2 to sp^3 carbon in Antarctic soils serves as a crucial indicator for understanding the composition, stability, and dynamics of soil organic in these distinct and harsh ecosystems. Antarctic environments are characterized by low temperatures, limited biological activity, and specific vegetation that shapes the organic material. In humic acids extracted from soils of Bunger Hills and Schirmacher Oasis, we found sp^2/sp^3 ratios of $0.42/0.58=0.724$ and $0.29/0.71=0.408$, respectively (Table 6). These results show that while there is significant aliphatic content (indicating potential for decomposition), there is also a notable presence of aromatic structures that contribute to soil stability over time. Previous research has shown that certain Antarctic soils possess significant amounts of stable organic carbon, indicated by elevated sp^2 levels (Beyer et al. 1997). This finding implies that these soils are capable of storing carbon effectively over extended periods, even in the face of limited biological activity. Our findings partly confirmed previous results (Beyer 1997; Pradel et al. 2023) showing the prevalence of aliphatic structure over aromatic in studied Antarctic soils; however they do not match perfectly with previously reported low levels of carbonyl groups. As mentioned above, in humic acids from topsoil of Bunger Hills Turbic Cryosol, where fresh C input was observed (probably from moss cushion), we could identify a low ratio of organic mineralization and a higher degree of humification.

Although there is a scarcity of literature regarding the molecular composition of soil organic matter (SOM) in Antarctic soils, our results are consistent with earlier studies from various regions of the continent, which showed that aliphatic carbon compounds are more prevalent than aromatic ones in typical organo-mineral soils (Calace et al. 1995). Additionally, recent research has revealed comparable traits in soils from different offshore oases. ^{13}C -NMR spectroscopy serves as an invaluable

tool for characterizing soil organic matter composition at a molecular level. The interpretation of chemical shifts allows researchers to infer structural features that govern biochemical processes within soils, ultimately contributing to our understanding of ecosystem functioning and resilience in polar regions facing rapid environmental change. By integrating ^{13}C -NMR data with other analytical techniques such as elemental analysis or isotopic studies, we can develop a more comprehensive picture of how Antarctic Cryosols contribute to global carbon cycles.

CONCLUSIONS

The research conducted in Bunger Hills and Schirmacher Oasis provides valuable insights into the unique soil characteristics, organic matter composition, and carbon dynamics within two remote inner shelf oases poorly investigated in the context of complex soil chemical and microbiological studies. Our work revealed a complex interplay between environmental conditions and soil characteristics that significantly influence biological activity, carbon storage, and the molecular composition of organic matter. Soils of East Antarctic oases have been investigated only sporadically, despite their fundamental importance for revealing information on soil genesis as well as ensuring the effective realization of environmental protection measures and saving unique ecosystems under the Antarctic Treaty System.

In both studied oases, the soils exhibited a range of physical-chemical properties shaped by factors such as moisture availability, salt accumulation, and vegetation cover. Notably, Turbic Histic Cryosol found beneath moss cushions demonstrated the highest levels of organic carbon and nitrogen accumulation. This is in line with previous soil research done in East Antarctica oases and suggests that microhabitats with moisture retention play a crucial role in supporting greater biological activity. We found pH values varying from slightly acidic to acidic conditions (under moss cushions), while alkaline conditions prevailed in areas affected by salt accumulation. Such variability highlights the significant impact of environmental factors on soil chemistry and biology. Higher TOC content was found in wet valleys. Soil respiration rates were generally lower in East Antarctic oases compared to other regions like King George Island, indicating limited biological activity due to the harsh climatic conditions prevalent in these areas. Our results demonstrated that soil moisture gradient (taking into account studied soil in wind shelters and dry flanks of the valleys) could play a critical factor for increasing carbon dioxide emission levels in harsh environmental conditions of East Antarctic oases. The general trend showed the highest values of basal respiration in wind shelters, followed by wet valleys, subaqueous soils on the lakes shoreline, and the lowest respiration rates in ahumic soils.

The molecular composition of humic substances was analyzed on two samples using ^{13}C -NMR spectroscopy, which revealed a predominance of aliphatic structures in humic acids extracted from studied samples from both oases. Although our preliminary results of ^{13}C -NMR

Table 6. The sp^2/sp^3 ratios of studied ^{13}C -NMR spectra of humic substances isolated from Antarctic Cryosols

Sample	sp^2/sp^3 ratio
Turbic Cryosol, Bunger 1 0–2 cm	0.724
Histic Turbic Cryosol, Novo 7 0–2 cm	0.408
Leonardite	2.11

spectroscopy showed predominantly common features of molecular composition of HAs with those previously described for other ice-free areas of Antarctica, other findings depicted lower levels of carbonyl carbon groups. This finding suggests ongoing microbial activity and organic matter decomposition processes that are critical for nutrient cycling in these cold environments. Significant peaks associated with carboxylic acids indicated that organic matter transformation processes are influenced by vegetation cover, particularly moss-lichen communities. We have observed a low ratio of organic mineralization and a higher degree of humification in topsoil from Bunger Hills (Turbic Cryosol), where fresh carbon input affected the spectral shape of ^{13}C -NMR.

The stability of soil organic matter is further underscored by the sp^2/sp^3 carbon ratios observed in humic acids from both Bunger Hills and Schirmacher Oasis. These ratios indicate a balance between aliphatic content – suggesting potential for decomposition – and aromatic structures that contribute to long-term stability. Such findings align with previous research indicating that Antarctic soils can effectively store stable organic carbon despite limited biological activity. By elucidating the physical-chemical

properties, molecular composition, and mineralization rates of soil organic matter, this study contributes to a deeper understanding of how Antarctic soils respond to environmental changes and their implications for greenhouse gas emissions. As climate change continues to impact these fragile ecosystems, future studies integrating various analytical techniques will be essential for enhancing our knowledge of their dynamics and resilience in an era of rapid environmental transformation.

Recent findings of our research project in Schirmacher Oasis (unexplored findings on influence of penguin colonies on soil formation in Schirmacher Oasis, Galustov et al. 2025), even more so, show the necessity of more detailed research in inner shelf oases to confirm or expand the ideas of soil formation, mineralization, and stability of organic matter previously accepted.

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