Laboratory assessment of soil respiration rates under the impact of ornithogenic factor in Antarctic region

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Abstract

SOM stabilization rates were estimated in the soils of Antarctic region in case of influence of ornithogenic factor. Soils in large penguin clusters, near nests of *Stercorarius sp.*, as well as soils located in geochemically subordinate positions (also often are visited by birds) were found to be characterized by an increased content of carbon and nitrogen with a rather narrow ratio of C/N. The pH values decreased in ornithogenic soils due to the organic acids that produced plants (mosses, *Deschampsia antarctica*) inhabit these soils and the decomposition products of the organic matter guano. The amount of CO_2, in general, released over the entire experiment period is quite large for both ornithogenic and non-ornithogenic soils. CO_2 emission rates were the highest in ornithogenic soils. Ornithogenic soils of the studied area are characterized by the most stabilized organic matter. Thus, the avifauna favors and increases the rate of the mineralization process by several times. An acceleration in the organic matter mineralization rate leads to an increase in nutrients amount available to plants, as in the case of the studied soils. The quality of initial SOM is of a great importance in post-ornithogenic environments. Therefore, further researches of CO_2 emissions rates are needed to characterize post-ornithogenic dynamics and develop an approach to model this process.

Keywords: Antarctic region, CO_2 emission, mineralization rate, ornithogenic factor, soil respiration.

Introduction

Soil organic matter (SOM) mineralization and CO_2 emissions from soil significantly influence on a global carbon cycle and ecosystem stability. For this reason, great attention has been paid to this topic already (Debasish-Sasha et al., 2014; Bruun et al., 2015; Muñoz-Rojas et al., 2015; Novara et al., 2015).

Soils of Arctic and Antarctic regions contain maximum SOM stocks within the whole pedosphere, therefore, they are of a great importance in global carbon circulation and stabilization (Schuur et al., 2015; Parras-Alcántara et al., 2015; Peng et al., 2015). At the same time, SOM stocks in the Antarctic region are underestimated along with the Arctic region. It is due to the data lack for many areas of this continent, due to the high content of stones in the soils and the carbon content high variability in the fine earth (Abakumov, 2010; Yu et al., 2012; Abakumov and Mukhametova, 2014; Wasak and Drewnik, 2015; Abakumov et al., 2016). Antarctic soils are different in their morphology, chemistry, texture and mineralogical composition (Abakumov et al., 2018; Dmitrakova and Abakumov, 2019) as well microbiome structure (Alekseev et al., 2020). Particularly, Antarctic soils have a low content of soil TOC but it is different in various areas and soils. Soil TOC content has a wide range: from minimum levels (close to 0%) in a humic regolith soils (Campbell and Claridge, 1987; Ugolini and Bockheim, 2008; Bockheim, 2013) to 3-4% in soils under mosses, lichens, and cereals (Simas et al., 2008; Abakumov, 2010), or in some areas formed under guano it reaches up to 30-40% of organic matter (Simas et al., 2007b).

Ornithogenic soils are a special type of soil formation that is characteristic primarily for ecosystems of the Southern Hemisphere (Abakumov, 2010), although these soils are regularly found in the northern polar biome (Ivanov and Avessalomova, 2012). Ornithochoria was shown (Parnikoza et al., 2016) to be quite important in plant remnants redistribution in the Antarctic region because a significant number of variably composed organic material are transported by birds within inland landscapes. Previously, a specificity in morphological structure of ornithogenic soils was established (Abakumov, 2014b), features of soils micromorphological and mineralogical composition under bird colonies were revealed (Abakumov, 2014a), and features of ornithogenic soils geography of the Northern and Southern hemispheres were shown (Abakumov, 2010; Abakumov and Lupachev, 2011/2012; Ivanov, 2013; Pereira et al., 2013), classification aspects were clarified (Parnikoza et al., 2015), and a development of soils in post-ornithogenic succession was described (Pereira et al., 2013; Abakumov, 2014b; Abakumov, 2018; Alekseev and Abakumov, 2018). However, further researches characterized SOM composition, its structural compounds and their distribution in Antarctic ornithogenic soils are needed as published data on this topic are rare.

Huge organic matter pools nowadays are affected to microbial degradation (Schuur et al., 2015) and other environmental risks (IPCC, 2007; Rein, 2013, Tsibart et al., 2014; Zaccone et al., 2014) due to global climate changes and subsequent upon it permafrost degradation. Polar environments SOM is a source of vulnerable carbon that is quite sensitive to remobilization because of increasing temperatures (Schuur et al. 2015; Ejarque and Abakumov, 2016).

Field and laboratory experiments (Zhao et al., 2012) are usually used for an evaluation of organic carbon mass emission loss. Possible mineralization losses from ornithogenic and non-ornithogenic soils can be assessed by controlled laboratory experiments. These methods are necessary for analysis of an apparent stability of SOM and its' mineralization losses and for prediction the possible stability and losses of organic carbon in soils of polar environments. At the same time, data obtained in controlled laboratory experiment and from field experiments (e.g., closed chambers method) are not comparable between each other. Nevertheless, data obtained in unified conditions can be used for further simulation modeling of SOM transformation.

The aim of this study is to investigate the soil organic matter mineralization (carbon mineralization rates and CO_2 emissions) in Antarctic soils of different origin by means laboratory incubation.

Material and Methods

Study sites

Soils subjected to a significant ornithogenic influence and non-subjected, were studied in terms of soil properties and CO_2 emission intensity: plots in large penguin clusters, near nests of *Stercorarius* sp., as well as plots located in geochemically subordinate positions (also often are visited by birds) and accumulating nutrients as a result of redistribution in the relief. The studies were carried out on King George Island (Fildes Peninsula) and on the specially protected natural area (SPNA) of Ardley Island (South Shetland Islands). A location of the sites is shown in Figure 1.

Figure 1. Location of study sites. Green circles – ornithogenic substrates, red circles – non-ornithogenic substrates.

King George Island is the largest island of South Shetland Islands archipelago (Figure 1). A relief of a southeastern part of the island is strongly dissected, has a number of bays. Most of the island is covered by a glacier. Numerous hills are composed of volcanic rocks (strongly eroded). According to eco-climatic zoning, King George Island refers to the Antarctic Peninsula in a part that is located north of the isotherm of average annual temperatures of -1°C. The island is located in the natural zone of Maritime Antarctica (Terauds et al., 2012). Soil formation is largely possible only at the tops of the hills and remnants, and also in the coastal parts characterized by a milder climate. Basalts, tuffs and andesites are parent materials, periglacial plots are covered by some fluvioglacial materials and moraines, while coastal areas are occupied by maritime sands

and gravels. Mosses, lichens, algae are typical for most of the island's habitats. In some parts of the island, two species of vascular plants occur – *Colobanthus quitensis* and *Deschampsia antarctica*. Seabirds, penguins and seals are abundant in habitats of the coastal island, and play a crucial role in soil development (Michel et al. 2006; Simas et al. 2007a).

Ardley Island is located on a south-west coast of King George Island, 500 m east of the Fildes Peninsula coast in Maxwell (Fildes) Bay. Mean annual air temperature (MAAT) at King George and Ardley Island is about -2.3°C; mean annual wind speed is 9.3 m/s; annual precipitation – 729 mm. The area is represented mainly by andesite-basalt lavas and tuffs belonging to the Tertiary. Several elevated terraces-beaches are also described. Due to high biodiversity of Ardley Island it is designated as Antarctic Special Protected Area (ASPA). A wide variety of seabirds arrive in the area during the breeding period (11 species) or molting. Ardley Island is also characterized by a highly developed and noticeable flora, including several species of vascular plants, lichens and mosses. The most common lichens at studied plots are *Usnea* gen. and *Himantormia lugubris*, as well as *Xanthoria* sp.*, Rinodina* sp.*, Placopsis* sp.*, Buellia* sp., *Haematomma* sp.*,* and *Caloplaca* sp., which occupied mostly the higher parts of Ardley Island.

Soil identification was carried out using the "Classification and Diagnostics of Soils of Russia" (2004) (Shishov and Tonkonogov, 2004) and the World Reference Base for Soil Resources (FAO 2015) (WRB, 2015). Both classification schemes can be applied to the soils of Antarctica, but are clearly insufficient to describe the entire diversity of soils in the region. The studied ornithogenic soils are distinguished by a specific morphological structure of the soil profile, which is often represented by the following set of soil horizons: peat horizon - organic dark gray or dark-brown horizon and median horizon. Characteristic of studied soil and their horizons are given in Table 1.

Table 1. Characteristic of studied plots and soils.

Plot	Depth, cm	Description	Soil horizons description
Ornithogenic soils			
Bel 12	0-2	The coast of Maxwell Bay, sand spit leading to Ardley island. The plot on the coast, covered by moss vegetation (20x30 m).	Peat horizon. Brownish color of plant debris. Low decomposition degree.
Bel 12	2-12	Soil name (WRB/RSCS): Histic Lithic Cryosol/Peat Lithozem underlain by permafrost	Brownish-grey horizon. The abundance of rounded boulders. Sandy loam.
Bel 14	0-2	Fildes Strait southwest coast. A vast (150x8 m) area covered with moss vegetation and reaching along the coast.	Peat horizon. Brownish color of plant debris. Low decomposition degree.
Bel 14	2-15	Soil name (WRB/RSCS): Histic Spodic Cryosol/Peat Cryoturbated Podbur underlain by permafrost	Dark grey horizon. The abundance of rounded boulders (5-20 cm). Sandy loam.
Bel 16	*Deschampsia antarctica*	CHN (Chinese Antarctic Program) monitoring site on top of a rocky highwall on the shore of the Drake Strait at the Biologists Bay. *Deschampsia antarctica* grows by curtains, moss cover grows sporadically. Fine detrital material is on the surface. Soil name (WRB/RSCS): Grey-Humus Lithic Cryosol/Grey-Humus Lithozem underlain by permafrost	Grey-humus horizon. Taupe. Medium-textured loam. Inclusion of rotted rock.
Bel 17	0-2	Surroundings of Bellingshausen Station, King George Island. Wet valley between rocky highwall.	Taupe horizon. Medium-textured loam. Lumpy and clumpy.
Bel 17	2-7	Waterlogging. A projective cover of moss cover is about 50 percent. Soil name (WRB/RSCS): Histic Stagnic Cryosol/Peat Gleyic Lithozem underlain by permafrost	Gley horizon with redoxymorphism signs. Glaucescent-gray with stripes of redoxymorphic material (mainly in the upper part of the horizon). Medium-textured loam. Lumpy structure.

Table 1. continue

Plot	Depth, cm	Description	Soil horizons description
Ornithogenic soils			
Bel 23	0-1	A mild hillslope in the central part of Ardley Island. A penguin nesting site is on a nearby rocky highwall.	Ornithogenic horizon. Grayish-glaucescent. Ornithogenic soil processing.
Bel 23	1-23	The surface is covered by alga *Prasiola crispa*. Soil name (WRB/RSCS): Post-ornithogenic Grey-humus Lithosol/Post-ornithogenic grey-humus Lithozem	Glaucescent-gray horizon. Less ornithogenic soil processing. Redoxymorphic signs appear in the lower part of the horizon.
Bel 24	Freshbar	The top of a weathered rocky highwall near lighthouses on the east coast of Ardley Island. The place of active life of the penguin colony. The surface is completely covered by guano layer. Soil name (WRB/RSCS): Turbic Ornithosol/Cryoturbated Ornithogenic soil	
Bel 25	0-1	East coast of Ardley Island. The surface is covered by moss vegetation (projective cover is about 70%).	Peat horizon. Brownish color of plant debris. Low decomposition degree.
Bel 25	1-4	Feathers of penguins and other birds are on the surface.	Dark grey-brown horizon. Traces of humus accumulation and accumulation of minerals subjected to ornithogenic impact. Sandy loam.
Bel 25	4-30	Soil name (WRB/RSCS): Post-ornithogenic Grey-humus Lithosol/Post-ornithogenic grey-humus Lithozem	Transition horizon to the parent rock. Dun color. Sandy loam. Inclusions of medium rounded rocky material.
Non-ornithogenic soils			
Bel 5	0-2	Small plot covered by mossy vegetation. Covers the surface of fine-grained material	Peat horizon. Brownish color of plant debris. Low decomposition degree.
Bel 5	2-16	Soil name (WRB/RSCS): Histic Spodic Cryosol/Peat Cryoturbated Podbur underlain by permafrost	Brown horizon. Sandy loam. Inclusions of small boulders.
Bel 26	0-1	Bellingshausen Station. Top of a flat hill. Moss-lichen cover. There are a lot of detrital material on the surface (40-50 cm).	Peat horizon. Brownish color of plant debris. Low decomposition degree.
Bel 26	1-6	Soil name (WRB/RSCS): Histic Spodic	Light brown-gray horizon. Sandy loam. Clarified lens as a sign of a podzolic (eluvial) process.
Bel 26	6-27	Cryosol/Peat Cryoturbated Podbur underlain by permafrost	Brown coffee color. Bfe horizon. Sandy loam.
Bel 27	0-5	Bellingshausen Station. The area between residential buildings and diesel power plant. Waterlogging. According to the drilling station, the permafrost is at a depth of 4 meters. Soil name (WRB/RSCS): Hyperskeletic Turbic Technosol/Cryoturbated Technozem underlain by permafrost	

Active layer thickness and dynamics in the studied area have been previously investigated. Permafrost table depths for the area of this study have been previously evaluated by vertical electrical resistivity sounding (Alekseev and Abakumov, 2020b). It was found that permafrost table lies at the depths of We found that permafrost table depth ranged between 89 and 100 cm in the area of our study.

Laboratory analyses

All chemical and biological parameters, described in the paper, were measured in soil fine earth, sieved through a 2-mm sieve. Standard soil analyzes (pH, C and N content) were performed according to conventional methods: C-H-N analyzer (Varie EL MAX, Elementar, Germany) were used for carbon and nitrogen content determination and pH was measured in solution – soil to water – with ratio of 1 : 25 (Vorobyova, 2006). A controlled laboratory incubation was carried out during the mineralization experiment. The experiment was carried out in five replicates for each soil horizon (collected from polypedones with an area of 2x2 m). CO_2 emissions were determined using the method described by Anderson (1982). Plastic cylinders 10 cm in diameter and 20 cm in height were used for work. 10 g in case of mineral soil and 5 g in case of organic material were placed in the cylinder during a controlled laboratory incubation. The cylinders with soil samples containing soil moisture of approximately 60% of water holding capacity were then placed in a beaker with a water at the bottom in order to simulate the field conditions of a paddy. The water content (%) was controlled during soil incubation. Then soil samples aliquots were brought at 20°C in sealed plastic bottles with 1 M NaOH. The amount of CO_2 trapped by an alkaline solution was measured by titration after 7 days of incubation. The incubation was carried out for 112 days.

Statistics

Data normal distribution was verified and a variance analysis (ANOVA) and post hoc test (Fisher's least significant difference) were performed. Differences were considered significant at $p < 0.05$.

Statistical data processing and analysis were carried out using standard methods in software packages MS Excel 2016, Past (version 3.20), Statistica 64 (version 10).

Results

General soil properties

The studied soils differ significantly in terms of C and N content (Table 2). The content of carbon increased due to the ornithogenic factor impact on the topsoil horizon. Upper horizons of ornithogenic soils have in average 4.5% C content while non-ornithogenic soils have less content of C in topsoil – 3.3%. Maximum of C content has samples of *Deschampsia Antarctica* and Freshbar (7.5 and 20% respectively). An accumulation of ornithogenic origin organic matter in humus horizons was also observed that unambiguously indicates the most important role of birds in the substances transfer from their coastal zone to the glacier surface. At the same time, organic matter does not remain "functionally dead", but, due to its dark color, promotes localized ice melting and the formation of microdepressions.

The C content, with regard to mineral horizons, was generally comparable to similar indicators at control plots. Decreasing of organic matter in lower soil horizons was observed both in ornithogenic and non-ornithogenic soils. Ornithogenic factor had a low impact on mineral horizons. Exactly the same picture is in case of N content: average values in upper horizons are 0.7 and 0.3% in ornithogenic and non-ornithogenic soils respectively. These data differ significantly ($p<0.05$).

This accumulation of organic matter of ornithogenic origin is confirmed by both an increased concentration of total organic carbon compared to non-ornithogenic soil samples, and a lower C/N ratio there – the most important indicator of the metabolism of any soil. The C/N ratio decreased two-fold in ornithogenic areas, because bird factor induced the organic residues mineralization. Thus, the ornithogenic factor affects not only soil formation in the traditional meaning (Parnikoza et al., 2015), but also the formation of soil-like bodies formed in places where cryoconites accumulate.

Analysis of pH_{H2O} values (water extract) in soils showed the predominance of close to neutral values ($5.6 <pH <6.5$) in humus horizons and weakly acidic ($5.1 <pH <5.5$) in lower horizons (under peat horizons) in case of ornithogenic soils; the predominance of neutral and close to neutral values ($5.6<pH<7.5$) in humus horizons and weakly alkaline and alkaline reactions ($7.0<pH<8.5$) in lower horizons in case of non-ornithogenic soils (Table 2).

It should be noted that the studied ornithogenic soils are characterized by significant acidification of the fine earth both due to the organic acids that produced plants (mosses, *Deschampsia antarctica*) inhabit these soils and the decomposition products of the organic matter guano.

Table 2. General soil properties.

Plot, depth, cm	C, %	N, %	C/N	pH_{H2O}
Ornithogenic soils				
Bel 12, 0-2	5.42±0.67	0.63±0.02	8.63	4.9
Bel 12, 2-12	3.98±0.45	0.42±0.03	9.48	5.9
Bel 14, 0-2	4.98±0.24	0.88±0.05	5.66	6.0
Bel 14, 2-15	2.32±0.78	0.43±0.05	5.40	6.9
Bel 16, Deschampsia antarctica	7.45±0.45	0.89±0.12	8.37	5.9
Bel 17, 0-2	5.32±0.21	0.53±0.03	8.10	6.0
Bel 17, 2-7	4.30±0.65	0.45±0.06	7.98	6.2
Bel 23, 0-1	4.31±0.23	0.53±0.03	8.10	5.9
Bel 23, 1-23	2.34±0.93	0.24±0.01	9.75	5.5
Bel 24, Freshbar	20.01±0.25	6.12±0.01	3.27	5.0
Bel 25, 0-1	1.56±0.32	0.22±0.02	7.09	5.5
Bel 25, 1-4	2.02±0.51	0.45±0.02	4.49	5.6
Bel 25, 4-30	1.02±0.05	0.12±0.01	8.50	5.4
Non-ornithogenic soils				
Bel 5, 0-2	3.54±0.12	0.40±0.04	8.85	5.7
Bel 5, 2-16	1.67±0.15	0.21±0.09	7.95	6.0
Bel 26, 0-1	3.31±0.67	0.38±0.11	8.71	5.8
Bel 26, 1-6	2.21±0.84	0.23±0.02	9.61	7.8
Bel 26, 6-27	1.02±0.54	0.12±0.03	8.50	7.0
Bel 27, 0-5	3.21±0.65	0.22±0.03	14.59	5.9
Post hoc test Ornithogenic soils – Non-ornithogenic soils	p<0.05	p<0.05	0.07	p<0.05
Singnificance of differences	Significant	Significant	Insignificant	Significant

CO₂ mineralization rates

Mineralization rates of soil organic matter in upper horizons of ornithogenic soils (Bel 12, Bel 14, Bel 24) turned out to be statistically significantly higher than in non-ornithogenic soils (p<0.05) (Table 3, Figure 2, 3). The cumulative production of C-CO₂ by the upper horizons of ornithogenic soils averaged 373.9 mg C-CO₂/100 g, by non-ornithogenic soils – almost 2.5 times less. Values of C-CO₂ cumulative production by the lower, non-surface horizons of ornithogenic soils were comparable to those of non-ornithogenic soils.

Table 3. Average CO₂ emission rates, mg CO₂/100 g soil/day.

Plot, depth, cm	Weeks				
	1-3	4-7	8-11	12-15	16-19
Ornithogenic soils					
Bel 12, 0-2	141.08	66.17	65.00	53.33	48.35
Bel 12, 2-12	24.04	31.58	27.05	24.90	19.08
Bel 14, 0-2	131.68	70.87	87.69	68.28	55.24
Bel 14, 2-15	21.96	19.24	32.25	20.99	16.26
Bel 16, Deschampsia antarctica	20.64	19.33	26.94	21.21	16.76
Bel 17, 0-2	15.16	13.44	15.69	17.69	20.27
Bel 17, 2-7	20.17	21.26	24.08	20.12	17.98
Bel 23, 1-23	39.03	32.64	45.57	43.16	26.14
Bel 24, Freshbar	84.72	62.52	73.08	55.82	51.72
Bel 25, 1-4	25.34	23.85	23.72	20.98	20.32
Bel 25, 4-30	31.62	23.18	32.83	24.83	18.43
Non-ornithogenic soils					
Bel 5, 0-2	66.88	54.46	84.77	66.32	51.67
Bel 5, 2-16	29.85	28.12	24.36	26.89	22.27
Bel 26, 0-1	87.27	79.87	86.03	84.60	62.85
Bel 26, 1-6	21.46	18.95	28.44	21.88	16.84
Bel 26, 6-27	21.97	20.54	23.81	25.09	17.90
Bel 27, 0-5	22.17	18.83	21.82	20.19	16.21
Post hoc test Ornithogenic soils – Non-ornithogenic soils	p<0.05	p<0.05	0.46	0.34	0.49
Singnificance of differences	Significant	Significant	Insignificant	Insignificant	Insignificant

The data obtained (Table 3) showed that the total amount of CO_2 released from the soil has 2 peaks over time: the first peak - at 1-3 weeks, at the very beginning of the experiment, the second peak - at 8-11 weeks. This tendency is typical almost for all studied soils of both ornithogenic and non-ornithogenic origin. The post-hoc test showed essential differences between ornithogenic and non-ornithogenic plots only for the first two experiment periods (1-3 and 4-7 weeks) ($p < 0.05$). The decrease in the rate of CO_2 release during the first month of soil samples incubation is apparently due to the consumption of easily available substrates. An increase in the rate of CO_2 production by soil horizons in the second half of the incubation period (3-4 months) is associated with the mineralization of inaccessible and deficient components (as sources of energy and nutrition) of soil organic matter by microorganisms.
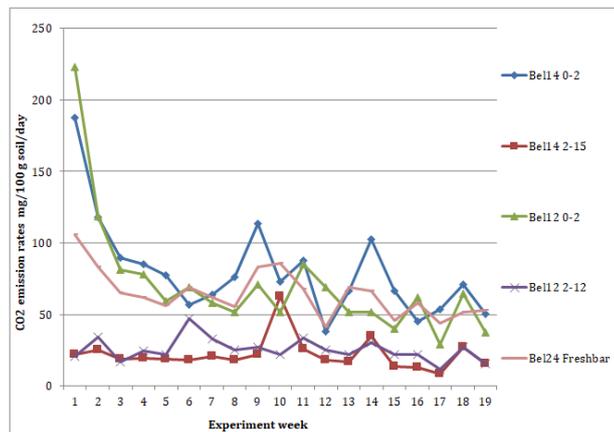

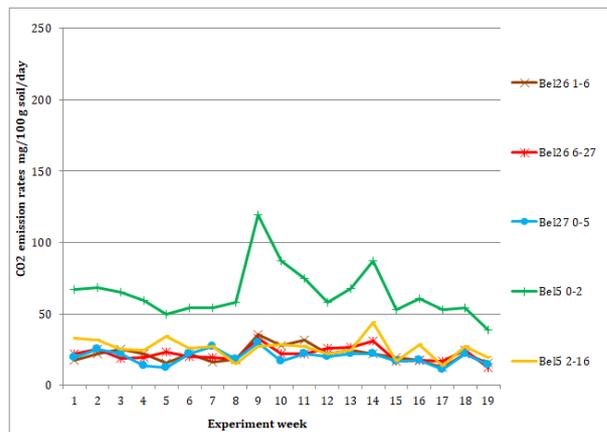Figure 2. CO_2 emission rates in ornithogenic soils, mg/100 g soil/day

Figure 3. CO_2 emission rates in non-ornithogenic soils, mg/100 g soil/day

CO_2 emission and SOM stability to mineralization

The amount of $C–CO_2$ produced by the incubated soil simultaneously characterizes both the metabolic activity of soil microorganisms and the ability of organic matter to mineralize. The content of potentially mineralizable carbon in the soil gives a general idea of the mineralization capacity of organic matter: the greater a proportion of potentially mineralizable carbon (PMC), the less stable soil organic matter and more susceptible to various mineralizing effects (Semenov et al., 2008, 2009; Kadono et al., 2009). The data on the rate of organic matter mineralization (Table 4) show that the total amount of CO_2 released from studied soil samples decreased over time. This tendency is more pronounced for upper soil horizons than for lower organo-mineral. A maximum of PMC content was found in the upper horizons of ornithogenic soils (Bel 12, Bel 14) (38.5 g/kg), while the proportion of potentially mineralizable carbon in the Bel 24 Freshbar soil, which has the highest C content ($20.01 \pm 0.25\%$), was 1.7 times lower (Table 4). The data of mineralization degree according to the $C-CO_2$ content (table 4), as well as in the case of CO_2 release intensity, show 2 peaks in time. The difference between $C-CO_2$/TOC ratio values were statisticaly significant for topsoil horizons (ornithogenic and non-ornithogenic) ($p < 0.05$).

The PMC percentage proportion of the total amount of organic carbon characterizes the mineralization capacity or stability of soil organic matter: the wider this ratio, the higher the stability of organic matter (Semenov et al., 2008; Kadono et al., 2009). The data obtained showed that ornithogenic soil (Bel 25) was characterized by the highest mineralization capacity - 84.69%. The mineralization capacity of the upper horizons in non-ornithogenic soils was, on average, lower than in ornithogenic soils. However, the opposite picture is observed for the lower horizons - ornithogenic soils are characterized by a reduced proportion of PMC in the total amount of organic matter. Therefore, a significant change of SOM quality occurs under the influence of the ornithogenic factor.

The stabilization of organic matter are the processes that increase its resistance to biotic and abiotic influences and lead to an increase in the turnover time of organic matter in the soil due to the acquired protected state. Destabilization is the reverse process of stabilization, as a result of which components of organic matter become less resistant to degradation and more available for microorganisms use (Swift, 2001; Six et al., 2006). The highest stability of organic matter was found for ornithogenic soils (Table 4). The rate of mineralization in lower mineral horizons of studied soils is lower than in surface horizons. Probably, the composition of soil humic acids (the ratio of carboxyl groups and aliphatic components) changes under the influence of the ornithogenic factor, which can cause a change in the mineralization rate of organic matter. Therefore, structural changes in the organic matter system under the influence of the ornithogenic factor play an essential role in the organic matter stabilization for soils (Ejarque and Abakumov, 2016).

Table 4. Portions of C mineralized on weeks and portion of total minerlized carbon to TOC content.

Plot	Depth, cm	C mineralized, gC-CO$_2$/kg soil fine earth, weeks					C-CO$_2$/TOC, %
		1-3	4-7	8-11	12-15	16-19	
Ornithogenic soils							
Bel 12	0-2	38.55	18.08	17.76	14.57	13.21	14.07
Bel 12	2-12	6.57	8.63	7.39	6.80	5.21	60.59
Bel 14	0-2	35.98	19.36	23.96	18.66	15.09	13.84
Bel 14	2-15	6.00	5.26	8.81	5.73	4.44	38.66
Bel 16	Deschampsia antarctica	5.64	5.28	7.36	5.80	4.58	132.14
Bel 17	0-2	4.14	3.67	4.29	4.83	5.54	128.45
Bel 17	2-7	5.51	5.81	6.58	5.50	4.91	78.07
Bel 23	1-23	10.66	8.92	12.45	11.79	7.14	21.94
Bel 24	Freshbar	23.15	17.08	19.97	15.25	14.13	86.45
Bel 25	1-4	6.92	6.52	6.48	5.73	5.55	29.18
Bel 25	4-30	8.64	6.33	8.97	6.78	5.03	11.81
Non-ornithogenic soils							
Bel 5	0-2	18.27	14.88	23.16	18.12	14.12	19.37
Bel 5	2-16	8.16	7.68	6.66	7.34	6.08	20.47
Bel 26	0-1	23.84	21.82	23.50	23.12	17.17	13.88
Bel 26	1-6	5.86	5.18	7.77	5.98	4.60	37.68
Bel 26	6-27	6.00	5.61	6.50	6.85	4.89	16.99
Bel 27	0-5	6.06	5.14	5.96	5.52	4.43	53.00
Post hoc test Ornithogenic soils – Non-ornithogenic soils		p<0.05	p<0.05	0.47	0.34	0.49	p<0.05
Singnificance of differences		Significant	Significant	Insignificant	Insignificant	Insignificant	Significant

Discussion

Soils exposed to ornithogenic factors showed significant differences in general chemical properties. Firstly, essential changes in the TOC content have been observed there due to a great role of guano organic matter in the soil-forming process. Non-ornithogenic soils are characterized by decreased nitrogen and carbon content, therefore it in turn increases C/N ratio compared to ornithogenic soil. These results correspond with data of Abakumov (2018) and Parnikoza et al. (2015), who showed a significant alteration in the quality of organic matter that occurs in post-ornithogenic soil. What is more, pH values decreased compared to ornithogenic soil because of organic acids that produced plants (mosses, *Deschampsia antarctica*) inhabit these soils and the decomposition products of the organic matter guano.

Cluster analysis was carried out in order to group studied plots according to the content of potentially mineralizable carbon in soils. Dendrograms of studied areas similarity are shown in Figure 4. Clustering was performed using a UPGMA method (unweighted pair group method with arithmetic mean). Cluster analysis, carried out using the Jaccard index and the single bond (nearest neighbor) method, identified two groups according to the principle of soil genesis: ornithogenic and non-ornithogenic soils (Figure 4), separately indicating the group of ornithogenic soils with the maximum rates of soil organic matter mineralization (Bel14 and Bel12). The merging of these two clusters occurs when the similarity rate is slightly higher than 50%. The noted soils grouping reflects the transformation processes specificity of organic substances in studied soils. Apparently, soils grouping is due to the predominance of organic matter transformation processes caused by the ornithogenic factor.

At the same time, a proportion of organic carbon mineralized during the experiment (%) was lower in non-ornithogenic samples than in ornithogenic ones. These data correspond with findings of Alekseev and Abakumov (2020a), who showed a significant alteration in the organic matter quality in post-ornithogenic soils. It has already shown that aromatic compounds portion is slightly more in soils formed on substances carried by birds compared to soils under monospecies of bryophytes or lichens communities (Abakumov and Fattakhova, 2015; Abakumov and Alekseev, 2018). This is explained by the fact that birds use mostly the *Deschampsia antarctica* remains for building nests, which contain an increased proportion of phenylpropane organic precursors (Alekseev and Abakumov, 2020a). This can affect the rate of SOM mineralization in post-ornithogenic and non-ornithogenic soils. Therefore, structural changes in a system of soil organic matter play an important role in its stabilization for post-ornithogenic soils, besides the SOM oxidation degree regulates mineralization rates and other indicators of the quality of post-ornithogenic SOM. Therefore, it can

be concluded that the most stabilized SOM is found for ornithogenic materials, where the humification degree and TOM transformation are the highest. Processes of organic matter stabilization begin immediately from the moment it enters the soil, where it undergoes destruction, decomposition and mineralization. Soil microorganisms are active agents not only for biodegradation of organic matter, but also for its stabilization. Thus, there are more microorganisms in ornithogenic soil that can lead to acceleration of mineralization rates and organic matter stabilization.
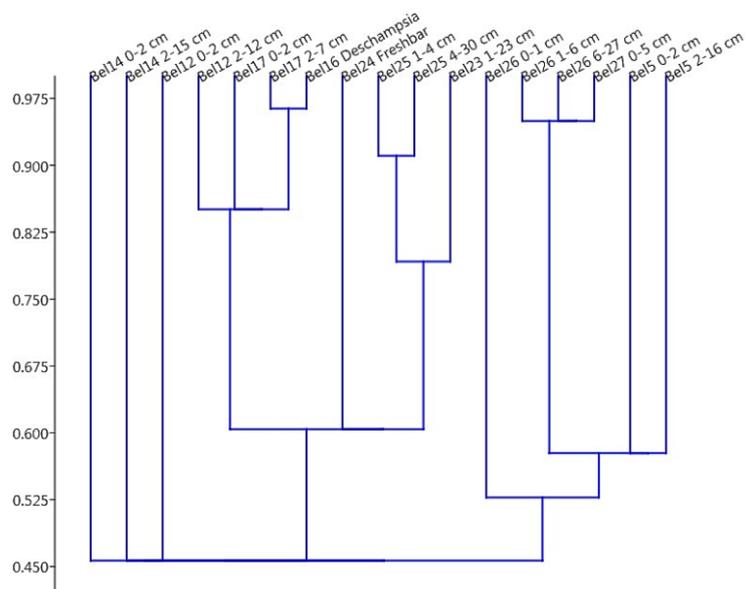
Figure 4. Dendrograms of studied areas similarity (Jaccard index, single bond (nearest neighbor) method).

Organic matter mineralization in soils occurs according to the various factors acting on them. On the basis of the results obtained, an attempt was made to identify the main environmental factors that determine the mineralization rate as a value on which these factors can have a direct effect.

The following factors, that could be assessed directly, or reflected in a certain gradation by expert assessment method, were identified:

— factors describing the genesis of the studied soils - the effect of the ornithogenic factor;
— factors describing the vegetation cover of the studied areas: moss-lichen cover, *Deschampsia antarctica* and guano, ornithogenic material;
— factors that describe soil characteristics and the depth of horizons: pH, C and N content, C/N ratio.

A degree of factors influence was assessed using the Canonical Correspondence Analysis (CCA) (Figure 5). Three factors that have the greatest impact on the rate of soil organic matter mineralization can be distinguished: pH, C content and origin (ornithogenic/non-ornithogenic soils). The depth of soil horizons influence on mineralization in lesser extent.
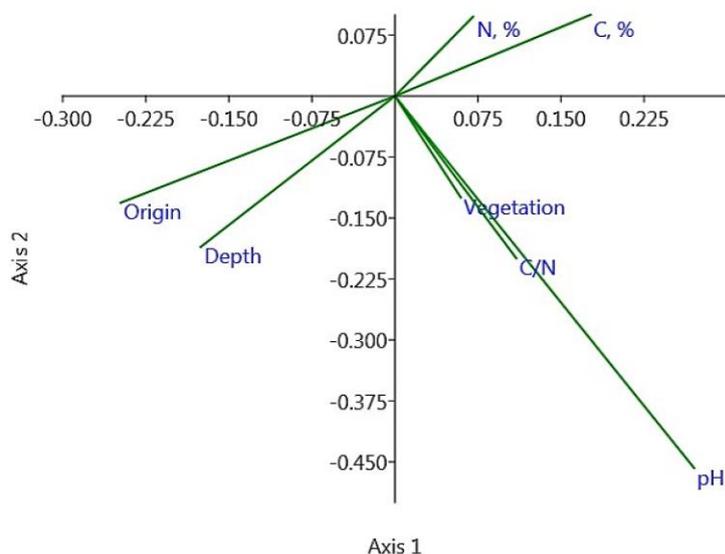

Figure 5. Environmental factors affecting the rate of organic matter mineralization in the studied soils.

Finally, results obtained suggest that additional laboratory incubation experiments are needed for investigation of various Antarctic post-ornithogenic environments in order to determine the role of the origin and quality of SOM and soil type in the rate of SOM stabilization and to better understand possible post-ornithogenic mineralization risks.

Conclusion

Soil processes in post-ornithogenic soils differ from those in not subjected to this factor soils. Study results indicate that soils under the current ornithogenic influence are characterized by an increased content of carbon and nitrogen with a rather narrow ratio of C/N. The amount of CO_2, in general, released over the entire experiment period is quite large for both ornithogenic and non-ornithogenic soils.

Comparing the resistance parameters of soil organic matter to mineralization, it can be concluded that the most stabilized organic matter is characteristic of ornithogenic soils of the studied area. Thus, the avifauna favors and increases the rate of the mineralization process by several times. An acceleration in the organic matter mineralization rate leads to an increase in nutrients amount available to plants, as in the case of the studied soils.

The accumulation of guano, nests building by penguins and other birds lead to the formation of specific soil polypedones. Apart from direct birds influence on soils localities of ornithogenic edaphotopes, their influence spreads through partial dissolution and substances migration in the landscape, nitrification, which leads to a post-ornithogenic successions start and a radical change in the local geochemistry of the landscape.

Therefore, ornithogenic soil formation is a special phenomenon of pedogenesis in the Southern Hemisphere, which expressed in the most diverse forms of morphological organization and processes of biogeochemical transformation. Thus, further study of CO_2 emissions is needed, with the aim of better characterizing post-ornithogenic SOM dynamics creating an approach to model this process.

Acknowledgments

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