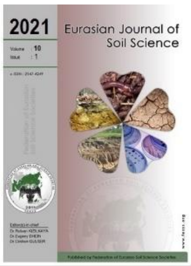
Eurasian Journal of Soil Science 2021, 10(4), 308 - 319

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



The role of the ornithogenic factor in soil formation on the Antarctic oasis territory Bunger Hills (East Antarctica)

Timur Nizamutdinov [a,*], **Mikhail Andreev** [b], **Evgeny Abakumov** [a]

[a] Saint-Petersburg State University, Faculty of Biology, Department of Applied Ecology, Saint-Petersburg, Russia
[b] Komarov Botanical Institute of the Russian Academy of Sciences, Saint-Petersburg, Russia

Article Info

Received : 01.04.2021
Accepted : 29.06.2021
Available online : 05.07.2021

Author(s)

T. Nizamutdinov *
M. Andreev
E. Abakumov

* Corresponding author

Abstract

The study focuses on the ornithogenic factor of soil formation in Antarctic conditions. Since the traditional soil formation processes in Antarctic conditions are very limited, the relevance of studying the role of the ornithogenic factor is increasing. This article provides a comparative study of nutrient content and values of some physico-chemical parameters between ornithogenic and non-ornithogenic soils sampled at terrestrial ecosystems of the Antarctic oasis Bunger Hills (Knox Coast, Wilkes Land). The levels of key biogenic elements content have been estimated with special reference to ornitogenic factor of soil formation. A high content of available forms of phosphorus and potassium in ornithogenic and non-ornithogenic soils was found. According to the results of statistical analysis, we can see that the content of nutritional elements has a close significant correlation relationship ($p<0.05$). The analysis of variance showed that the content of available phosphorus and potassium varies weakly between soils of ornithogenic and non-ornithogenic genesis. The greatest variability depending on soil-forming processes is noted for basal respiration, pH and available forms of nitrogen.

Keywords: Antarctic soils, ornitogenic soils, nutrients.

Introduction

The investigation of the soil cover of the Antarctic continent and subantarctic islands is basically aimed to understanding and estimating the dynamics of anthropogenic impact and the current condition of soils in the vicinity of the Antarctic Research Stations. There are numerous works devoted to the assessment of chemical pollution of soils and soil-like bodies in the territory of Bellingshausen (Abakumov et al., 2014), Scott Base (Saul et al., 2005), McMurdo (Campbell et al., 1998), Russkaya, Leningradskaya, Akademik Fedorov (Abakumov et al., 2014) stations and their vicinities. The soils of King George Island (Vlasov et al., 2005), Livingston Island (Kostova et al., 2015), the Schirmacher Oasis (Lepane et al., 2018), the South Shetland Islands , the Larsemann Hills (Mergelov, 2014), and many other areas free of cover glaciation, which are subjected to anthropogenic influence in scientific research of various kinds, have been extensively studied.

The soils of the continental ice-free part of Antarctica, where there are no permanent research stations, are much less studied due to the inaccessibility of these territories and the extreme climate conditions (Beyer et al., 2000; Hopkins et al., 2006; Zazovskaya et al., 2015). Although it is possible that it is in isolated areas that take place unique and unexplored to this day processes of soil formation. The surface area of ice free zones,

doi : https://doi.org/10.18393/ejss.962538
: http://ejss.fesss.org/10.18393/ejss.962538
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

or as they are often called - Antarctic Oasis's, is variates from 1 to 5% of the whole territory of the Sixth Continent (Dolgikh et al., 2015).

Soil zonal distribution in Antarctica is traceable only in sub-Antarctic (including island) and coastal territories; in the continental part, the soil cover is represented by intrazonal soil formations of different genesis (Campbell and Claridge, 1987; Bockheim and Hall, 2002). One of the essential factors for the existence of soil zonality in Antarctica is the degree of moisture supply; the moistest places inhabited by various mosses and lichens are the areas of soil formation in its classical sense (Ugolini and Bockheim, 2008).

Goryachin (2012) notes that Antarctica as a whole has no complete soil cover, and identifies so-called "pedospheric islands" that are not influenced by Latitudinal Zonation and their development depends more on "pedospheric islands" size and the influence of glaciers on them (Goryachkin, 2019). Some researchers have an opinion that the ahumic – according to Tedrow (1966) soils of Antarctica are not "true" soils, in the classical sense laid down by Dokuchaev and his predecessors (Tedrow and Ugolini, 1966).

The main argument is that these soils are weakly developed in terms of solum differentiation and have no real genetic horizons of organic matter accumulation, which is characteristic of "true soils" and are mechanically mixed substrates of mineral sediments and organic matter of zoogenic genesis. However, even if one agrees with the argument, these formations can be classified as soil-like bodies (Goryachkin, 2019) (typical for formations of aeolian origin on glaciers - cryoconites), based on the works of Sokolov, Goryachin, Targulyan (Targulyan, 1971; Sokolov, 1993; Goryachkin, 2019; Goryachkin et al., 2019).

Broadly speaking, the soil cover of the Antarctic continent is characterized by a hyperskeletic texture with a predominance of coarse grained fractions and a high sand percentage in the fine earth (Bockheim, 2014).

Although erosion and aeolian process are the main soil forming process in Antarctica (Abakumov, 2011), there are less pronounced processes, particularly the processes of organic matter accumulation and alteration of mineral components (Antarctic tundra), also the processes of salinization and cryoturbation (Antarctic deserts) (Glazovskaya, 1958, Bockheim, 2015), as well as the processes of endolithic soil formation (Mergelov et al., 2012).

Coastal areas are characterized by processes of formation of subaquatic soils, caused by periodic or permanent underflooding of local erosion bases, as a result of thawing of the glacial cover (Nikitin and Semenov, 2020). The existence of large colonies of various bird species (penguins, skuas, petrels) is the cause of zoogenic or ornithogenic soil formation, which is observed not only in coastal areas, but also in continental ecosystems isolated by glaciers (Heine and Speir, 1989; Emslie et al., 2014; Abakumov et al., 2016; Abakumov et al., 2019).

The ornithogenic factor of soil formation in Antarctic conditions is, in our opinion, one of the most interesting. Ornithogenic soils are the result of specific processes of zoogenic soil formation, which is characteristic mainly for the ecosystems of the southern hemisphere (Syroechkovsky, 2019). Climatic conditions are limiting the processes of humification in the classical sense, since the vegetation cover of the continent is represented by spots of distribution of lower plant-forms in the most humid areas (Abakumov, 2019).

Under conditions of deficit of organic matter of plant formation, accumulation of organic matter in the soil profile is possible during zoogenic-ornitogenic soil formation processes (Heine and Speir, 1989; Simas et al. 2007). Especially relevant are these processes in isolated areas of continental Antarctica or on the islands of the Subantarctic. The origin of ornithogenic soils is caused by the transformation of bird food into organic matter, followed by the transfer of this substance to nesting sites and accumulation in the soil cover in the form of guano (Ugolini, 1972; Abakumov, 2014b).

Ornithogenic soils are intrazonal and their formation strongly depends on the population of birds and the specifics of their migratory activity (Parnikoza et al., 2015). Birds, by transferring the genetic material of small invertebrates and plants, provide an opportunity for the development of mosses, lichens and algae to grow in isolated Antarctic oasis (Parnikoza et al., 2012; Abakumov et al., 2020b).

The most important of the features of ornithogenic soil formation depend on the character of the terrain on which guano accumulates. The process of migration of organic matter of ornithogenic origin on loose bedrock allows absorption of the lowest soil horizons and active mineralization across the full soil profile. On higher-density crystalline rocks, the processes of vertical migration are limited, resulting in the formation of a large ornitokoprogenic horizon weakly influenced by mineralization. The intensity of mineralization is the higher the more the content of fine-grained material in the underlying rocks (Abakumov, 2019; Lupachev and Abakumov, 2013; Alekseev and Abakumov, 2020).

According to some researches devoted to ornithogenic soil formation in Antarctic conditions, it is noted that biogenic processes in ornithogenic soils contribute to the accumulation of Phosphorus Forms in the soil profile (Simas et al., 2007).

The processes of ornithogenic soil formation cardinally alter the morphological structure of the soil profile. It is important to note that soils formed under the influence of the ornithogenic factor cannot be classified as "soil-like bodies", since mineralization of organic matter and formation of organogenic horizons in the soil profile take place (Abakumov, 2014a).

This article is aimed to identify the chemical parameters of ornitogenic factor of soil formation on the territory of the Bunger Hills oasis (Antarctica, Wilkes Land, Knox Coast). To identify the significance of ornithogenic soil formation, we conducted a set of laboratory analyses of soil samples. And using statistical methods, we tried to identify differences between ornithogenic and non-ornithogenic intrazonal soils.

Material and Methods

Regional setting

The Bunger Hills are an ice-free region of low hills and deep glacial lakes covering 400 km^2 along the coast of Wilkes Land, East Antarctica (located at approximately 100°45’ E, 66°17’ S), and separated from the Southern Ocean by the Shackleton Ice Shelf. Its total area including marine basin and islands is about 950 km^2 (length – ca. 50 km, width – ca. 20 km) (Tucker et al., 2017).

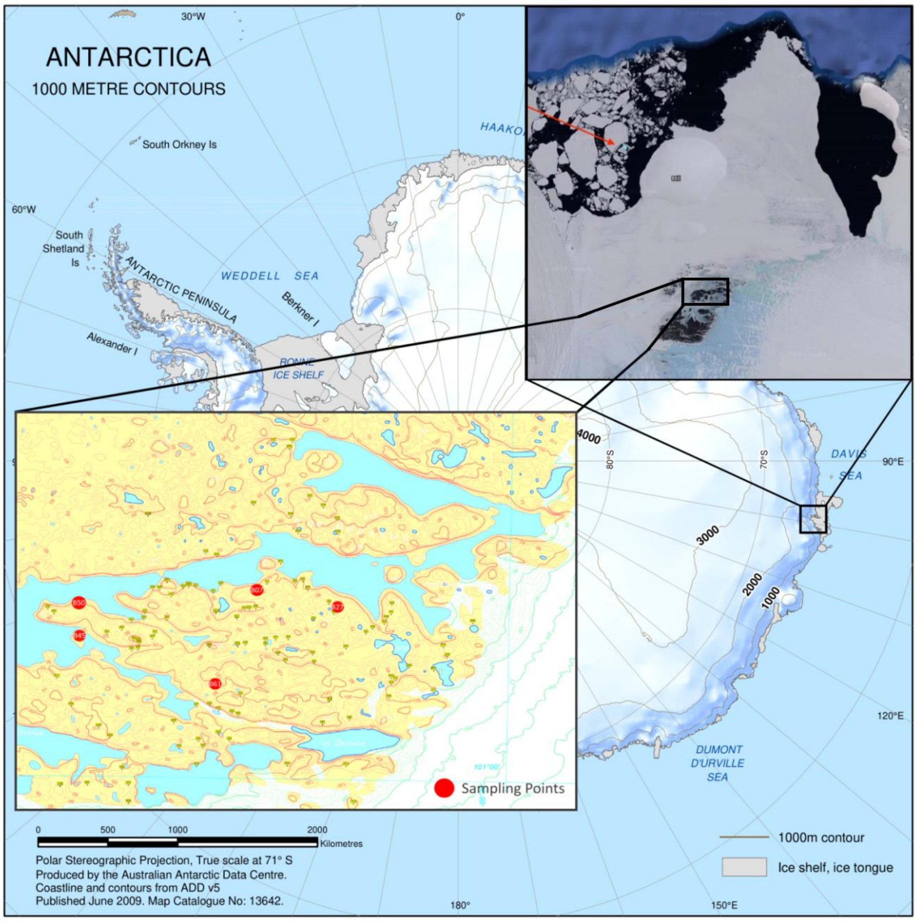


Figure 1. Sampling site map

The field work was conducted at the south-eastern side of the mainland’s part of the Bunger Hills oasis between big and long lake Figurnoe and the ice cap (Figure 2). The work of the field party was organized by the Polar Marine Geosurvey Expedition" (PMGE) during 65 Russian Antarctic Expedition (30.12.2019-14.03.2020). Soil samples collecting was made contemporary with the investigation of the lichen flora and vegetation of the oasis as an extension of previously made study (Andreev, 1990 and in prep.).

Rocks on the cost of subglacial lake Hilly landscape near Tikhoe Lake

Depression with small lake in lake's valley Field camp near small lake

Figure 2. Bunger Hills. (Photos: M. Andreev).

40 soil samples (21 ornithogenic and 19 non-ornithogenic) were collected in 5 sampling sites. Detailed map of points and sampling sites characteristics can be seen in Figure 1 and Table 1.

Table 1. Sampling site characteristics

Sample code	Plot name	Sampling site description	Meters above sea level	S	E
B07	Antarctica, Wilkes Land, Knox Coast, Bunger Hills	Land to the South of the Lake Figurnoe, a rock ca. 6 m high, with a nest of snow petrel in crevice.	52 m	66 18.171	100 54.280
B27	Antarctica, Wilkes Land, Knox Coast, Bunger Hills	Land to the South of the Lake Figurnoe,, "Lakes Valley", small depression between rocks, flat bottom, a nest of snow petrels in rocks.	71 m	66 18.315	100 56.088
B45	Antarctica, Wilkes Land, Knox Coast, Bunger Hills	Land to the South of the Lake Figurnoe, gentle slope of the hill on an isthmus to the "Black Peninsula", moraine, feeding place of skuas.	19 m	66 18.614	100 50.211
B50	Antarctica, Wilkes Land, Knox Coast, Bunger Hills	Land to the South of the Lake Figurnoe, hill's top on long peninsula, black rocks, nest of snow petrels.	61 m	66 18.293	100 50.206
B61	Antarctica, Wilkes Land, Knox Coast, Bunger Hills	Land to the South of the Lake Figurnoe, at the river between lakes Dalekoe and Figurnoe, the rock on hill's top, southern slope, nest of snow petrel.	125 m	66 19.064	100 53.335

All samples during the field seasone were saved in plastic bags in box on fresh air at external temperature (first – from 0 to +3-5°C, later – below zero), and transported to Saint-Petersburg university laboratories within scientific vessel "Akademik Fedorov" at the temperature below zero. After air drying all the samples were grounded and passed through a 2 mm mesh screen.

Oceanites oceanicus (Wilson's storm petrel), *Pagodroma nivea* (Snow petrel) *Stercorarius maccormicki* (South polar skua) are the following bird species that inhabit the Bunger oasis (Leishman et al., 2020).

Pagodroma nivea nests found anywhere in southern Bunger Hills where crevices are present in cliffs (Gibson, 2000). As Bulavintsev (1993) notes, the population of *Pagodroma nivea* in the banger oasis numbers more than 1,000 individuals (Bulavintsev et al., 1993), and their nests are characterized by the characteristic accumulation and solidification of petrel stomach oil for this species (Hiller et al., 1995).

Stercorarius maccormicki are highly visible, as they are relatively large, congregate in small groups and are noisy. Gibson (2000) estimated that there were about 50 individuals in the banger oasis (Gibson, 2000). Most often they can be spotted in feeding areas where many feathers and remnants of their prey (petrel shells) are scattered. Some most typical of the identified bird habitats (at the sampling sites) are presented in the Figure 3.


B45 - place of feeding of skuas
B07 - nest of snow petrel in crevice


B50 - nest of snow petrels
B61 - nest of snow petrels

Figure 3. Birds habitat places in Bunger Hills

Oceanites oceanicus nests are mainly located at a height and are hidden in crevices and folds of the terrain. Therefore, sampling of ornithogenic soils was carried out directly near the nesting sites from a depth of 7 - 10 cm, and background (non-ornithogenic) soils were sampled down the slope at a distance of 15 - 20 meters from the nesting sites. A large amount of organic material was found at the *Stercorarius maccormicki* feeding sites, so background samples of non-ornitogenic soils were sampled at a distance of 50 - 100 meters.

Laboratory analysis

All laboratory activities on chemical and physical analysis of soil were conducted at 22.5°C in soil fine earth. Basal respiration of soil was estimated by measuring CO_2 in Sodium Hydroxide. Incubation of CO_2 was conducted for 10 days in plastic sealed containers (Jenkinson and Powlson, 1976). The pH of soil was determined by potentiometric method using pH-meter (pH-meter - millivolt meter pH-150MA, Belarus). Soil solution was prepared in the ratio of 1:2,5 with water or 1M $CaCl_2$ (for mineral soils the optimal soil weight for solution preparation is 8 g) (Black, 1965). The particle size distribution of the soil was determined by the sedimentation method (Jackson and Saeger Jr, 1935; Kachinskiy, 1958). The texture class of soil was determined on the base of particle size disctribution analyzes.

Key parameters of soil nutrient state have been determined by the standard procedures recorded in GOST 54650–2011 (for evaluation of available phosphorus and potassium contents) and GOST 26489–85 (for evaluation of ammonium nitrogen content). The procedure for measuring ammonium nitrate requires its extraction from the soil with potassium chloride solution. Quantitative determination of ammonium is carried out using photometry of colored solutions (EPA, 1993). The determination of the available forms of phosphorus and potassium is based on the extraction of the compounds described above with hydrochloric acid (acid concentration 0.2 mol/L). After extraction, the quantitative determination of mobile phosphorus and potassium compounds is carried out by photometry methods (Sparks et al., 2020).

Total organic carbon and nitrogen were determined with a C-H-N analyzer (Euro EA3028-HT, Italy) of Research Park at St. Petersburg University.

Results and Discussion

Key chemical and physical properties of soil samples

The results of the laboratory analysis of soil samples are shown in Table 2. Based on the data obtained on basal respiration of soils, acidity, and nutrient content, it is not possible to conclude findings about cardinal differences between ornithogenic and non-ornithogenic soils. The terrain in the areas adjacent to the glacier is shallow, deeply dissected, in the southern and western parts is more smooth. The highest altitude is 168 m above sea level. Prevailing heights 50-80 m above sea level. The ridges and slopes of hills are covered with loose eluvial-deluvial and moraine deposits (Simonov, 1971).

Table 2. Chemical and physical properties of soil samples

Sampling code	Sampling point	Basal respiration, CO_2/100g soils per day	pH (H_2O)	pH ($CaCl_2$)	Available		NH_4-N	NO_3-N	Particle-size distribution
					P	K			
					mg kg^{-1}				
Non-ornitogenic soils									
B27	NR2/10	69.14	8	nd	801	203	6.46	1.05	Loamy Sand
	NR2/11	69.14	7.96	nd	1083	263	12.3	1.98	
	NR2/7	88.00	8.85	nd	726	217	3.26	3.03	
	NR2/8	56.57	8.46	nd	863	341	12.8	7.64	
	NR2/9	37.71	8.55	nd	946	230	4.59	0.79	
B45	NR3/10	69.14	9.71	nd	797	304	4.8	1.62	Sandy Loam
	NR3/11	69.14	7.89	nd	759	737	5.39	7.16	
	NR3/7	81.71	8.6	nd	635	350	7.95	1.84	
	NR3/8	56.57	8.26	nd	693	415	10	19.4	
	NR3/9	37.71	8.72	nd	755	433	15.3	5.93	
B50	NR4/10	31.43	7.8	nd	851	309	16.5	2.55	Loamy Sand
	NR4/11	94.29	8.57	nd	913	359	7.63	4.65	
	NR4/7	69.14	8.25	nd	747	290	4.48	1.45	
	NR4/8	56.57	7.59	nd	875	244	12.6	2.2	
	NR4/9	37.71	8.44	nd	780	392	11.8	5.84	
B61	NR5/10	62.86	7.47	nd	1390	341	12.1	8.96	Loamy Sand
	NR5/11	75.43	6.55	4.28	929	382	5.76	2.55	
	NR5/7	62.86	6.74	5.81	913	194	6.4	0.97	
	NR5/9	56.57	7.31	nd	15870	852	754.1	18.9	
Ornitogenic soils									
B27	OR2/1	94.29	8.25	nd	763	253	10.8	3.42	Loamy Sand
	OR2/2	62.86	8.05	nd	1407	134	34.4	10.1	
	OR2/4	75.43	7.55	nd	938	369	10.6	6.24	
	OR2/3	37.71	8.25	nd	730	143	8.7	1.89	
	OR2/5	119.43	6.24	5.8	1232	235	25.8	22.2	
B45	OR3/1	56.57	7.86	nd	1075	401	19.2	15.9	Sandy Loam
	OR3/2	100.57	7.22	nd	813	276	19.3	12	
	OR3/3	56.57	8.33	nd	1083	212	22.9	17.6	
	OR3/4	62.86	7.56	nd	639	143	3.36	7.11	
	OR3/5	69.14	7.91	nd	1212	359	26	37.3	
B50	OR4/1	69.14	8.15	nd	1091	322	6.62	11.2	Sandy Loam
	OR4/3	75.43	7.75	nd	751	226	14.8	5.31	
	OR4/4	169.71	8.32	nd	1469	433	7.85	17.4	
	OR4/5	106.86	7.58	nd	950	253	9.18	1.93	
	OR4/2	50.29	8.13	nd	1311	364	12.5	15.9	
B61	OR5/1	75.43	4.4	3.5	1274	157	56.6	13.4	Sand
	OR5/2	106.86	5.26	4.61	3303	392	321.3	26.1	
	OR5/3	69.14	5.74	4.59	2377	382	283.9	19.8	
	OR5/4	69.14	5.76	5.61	8525	1290	714.1	60.9	
	OR5/5	88.00	5.52	3.98	1909	115	36.3	7.33	
	OR5/8	37.71	6.63	5.22	838	138	28.1	4.83	

The level of soil basal respiration variates sharply in all the obtained data, no clear differences in the level of CO_2 emission depending on soil type are observed. Several local minimums and maximums for soil types are identified. For non-ornitogenic soils, the maximum basal respiration value is 94.29 mg CO_2/100g soil per day (sample NR 4/11, area B50), and the minimum is 31 mg CO_2/100g soil per day (sample NR 4/10, area B50). For soils of ornithogenic genesis, the highest soil CO_2 emission level was 169.71 mg CO_2/100g soil per day (sample OR 4/4, zone B50) and the minimum was 37.71 mg CO_2/100g soil per day (sample OR 2/3, area B50). It is important to note that the minimums and maximums of soil respiration levels occur in the same sampling area (B50).

Non-ornitogenic soils are characterized by predominantly alkaline and weakly alkaline reaction (the average value of pH H_2O 8.09 for all nonornitogenic soil samples). The dynamics of acidity reaction for soils of ornithogenic genesis is rather different. From strongly acidic and weakly acidic (pH H_2O 4.4 – 6.63) B61 area to weakly acidic and weakly alkaline (pH 5.8 – 7.62) in all other samples. pH in salt suspension were lower (by 1 on average) for all soil samples, which may indicate a reserve of acidity in soil colloids, associated with the processes of destruction of organic matter (Thomas, 1996).

Among the major nutrients, the most notable is the content of available phosphorus in all soil samples. The concentration of phosphorus varies greatly (635 – 15870 mg×kg^{-1}), interestingly, the highest concentration was recorded in soil of non-ornitogenic genesis (15870 mg×kg^{-1}, sample NR 5/9 area B61). We can also note a high content of available phosphorus in ornithogenic soils of predominantly sandy particle size distribution (area B61). Some researchers have already noted an increased content of available phosphorus in ornithogenic soils and noted the formation of phosphorus - containing minerals in them (Tatur and Barczuk, 1985; Tatur and Keck, 1990; Simas et al. 2007; Abakumov, 2018). In works devoted to the influence of birds on soil formation noted that the high content of available forms of phosphorus and potassium is one of the main signs of the processes of ornithogenic soil formation (Simas et al. 2007; Simas et al. 2008; Abakumov et al., 2021).

The content of available potassium is also highly variation (115 – 1290 mg kg^{-1}). The maximum values were recorded in the ornitogenic soil of sandy particle size distribution (1290 mg kg^{-1} sample OR5/4, area B61).

It should be noted 2 soil samples with extremely high content of nutrients, these are samples NR5/9 and OR5/4 in area B61 of non-ornithogenic and ornithogenic genesis, respectively. In these soils the content of available forms of phosphorus, potassium and nitrogen is the highest, in comparison with all other soil samples studied, at that they have different character of soil formation, presumably.

We have calculated C/N ratios for estimation of levels of soil organic matter enrichment by nitrogen. This value reflects the influence of many factors on the soil, especially climate and soil formation features (Miller et al., 2004; Yamashita et al., 2006; Lou et al., 2012). Thus, the lower the ratio, the higher the enrichment of the soil with nitrogen. Since for this territory the nitrogen inflow is mainly due to the influence of ornithogenic factor, the C/N ratio for this territory can be used as an indicator of the degree of activity of ornithogenic soil formation.

The C/N value allows one to understand what processes are currently occurring in the soil, mobilization or mineralization. It is known that at the $C/N < 20$ the processes of nitrogen mineralization prevail, and at the $C/N > 30$ there is immobilization of nitrogen in the soil profile (Janssen, 1996; Semenov, 2020). However, this classification is more applicable to soils in their classical sense, in primitive ahumic soils the C/N ratio can be used to estimate the degree of nitrogen deficiency. As can be seen from Table 3, for most of the investigated soil samples the C/N ratio is essentially lower than 20, except for samples OR4/2 and OR5/4 for which the values are 22.2 and 28.78, respectively. The low values of the C/N ratio are explained by the inflow of nitrogen into the soil due to the influence of the ornithogenic factor, as shown in Table 2, soils are quite rich in nitrogen compounds.

Based on the results, we can conclude that there is no nitrogen deficiency in almost all of the studied soils in the study area. Low ratio values indicate significant nitrogen input to the soil.

Statistical analysis

Based on the obtained data set on the content of soil nutrients, basal respiration and soil pH, Spearman rank correlation coefficient matrix was calculated (Table 4).

As can be seen from the table above, a significant correlation is observed between the various nutritional elements. The strongest correlation was found between available phosphorus and ammonium nitrogen content, as well as between anmonium and nitrate nitrogen content.

Table 3. C and N content of soils and C/N ratio values.

Sampling area	Soil samples	C, %	N, %	C/N*
		Non-ornitogenic soils		
B45	NR3/10	0.42	0.14	2.97
	NR3/11	1.21	0.91	1.32
	NR3/9	0.22	0.04	5.03
B50	NR4/10	1.47	0.43	3.38
	NR4/7	1.42	1.14	1.25
	NR4/8	1.18	0.91	1.29
B61	NR5/7	1.44	1.12	1.28
	NR5/9	2.80	1.49	1.88
				Ornitogenic soils
B27	OR2/2	0.31	0.08	3.59
	OR2/5	3.00	1.16	2.59
B45	OR3/1	0.26	0.11	2.25
	OR3/2	1.60	1.04	1.54
	OR3/3	0.11	0.05	1.96
	OR3/4	0.98	0.86	1.14
B50	OR4/5	1.23	0.81	1.52
	OR4/2	0.22	0.01	22.20
B61	OR5/1	2.36	0.44	5.39
	OR5/2	3.33	0.51	6.50
	OR5/3	1.37	0.41	3.41
	OR5/4	3.19	0.75	4.12
	OR5/5	0.57	0.02	28.78
	OR5/8	0.44	0.14	2.99

* - mass ratio

Table 4. Spearman Rank Order Correlations Marked correlations are significant at $p < 0.05$

	Basal respiration	Available Phosphorus	Available Potassium	Ammonium Nitrogen	Nitrate Nitrogen
Basal respiration	1.00				
Available Phosphorus	0.17	1.00			
Available Potassium	0.00	0.18	1.00		
Ammonium Nitrogen	-0.05	0.62	0.10	1.00	
Nitrate Nitrogen	0.13	0.58	0.42	0.67	1.00

Analysis of the mean values by ANOVA (Table 5 and Figure 5) revealed significant differences for all the obtained soil parameters depending on the genesis of soil formation. Significance was confirmed by Fisher's test with a P value of 0.0007.

Table 5. ANOVA Multivariate Tests of Significance. Sigma-restricted parameterization. Effective hypothesis decomposition

	F	p
Ornitogenic vs non-ornitogenic	4.9592	0.0007

More detailed differences between the average values of all studied soil parameters are presented in Figure 4. The variability of the mean values clearly shows that the main contribution to the overall variability is made by the parameters of basal respiration, pH (H_2O) and the content of ammonium and nitrate forms of nitrogen. The average content of available phosphorus and potassium practically does not change depending on the genesis type of soil formation.

Conclusion

A Lithovit treatment as foliage nutrition at a 6 g/L rate combined with an irrigation level of 100% ETc Data obtained, showed that the processes of ornithogenic soil formation on the territory of the Bunger oasis have a fingerprint in both types of location: directly and indirectly faced to geochemical effect of birds. All the soils surveyed are characterized by high content of available forms of nutrients, which is typical for ornithogenic soils. The high content of available phosphorus, whose high concentrations in ornithogenic soils were also recorded by other researchers, is particularly remarkable. Non-ornitogenic soils are characterized by predominantly alkaline and weakly alkaline reaction of the soil solution The soil solution reaction of ornithogenic soils is more variable, ranging from strongly acidic to weakly alkaline. Soils of sandy texture type are characterized by an acidic reaction of the soil solution. Based on the C/N values, we can conclude about no nitrogen deficiency in the studied soils.

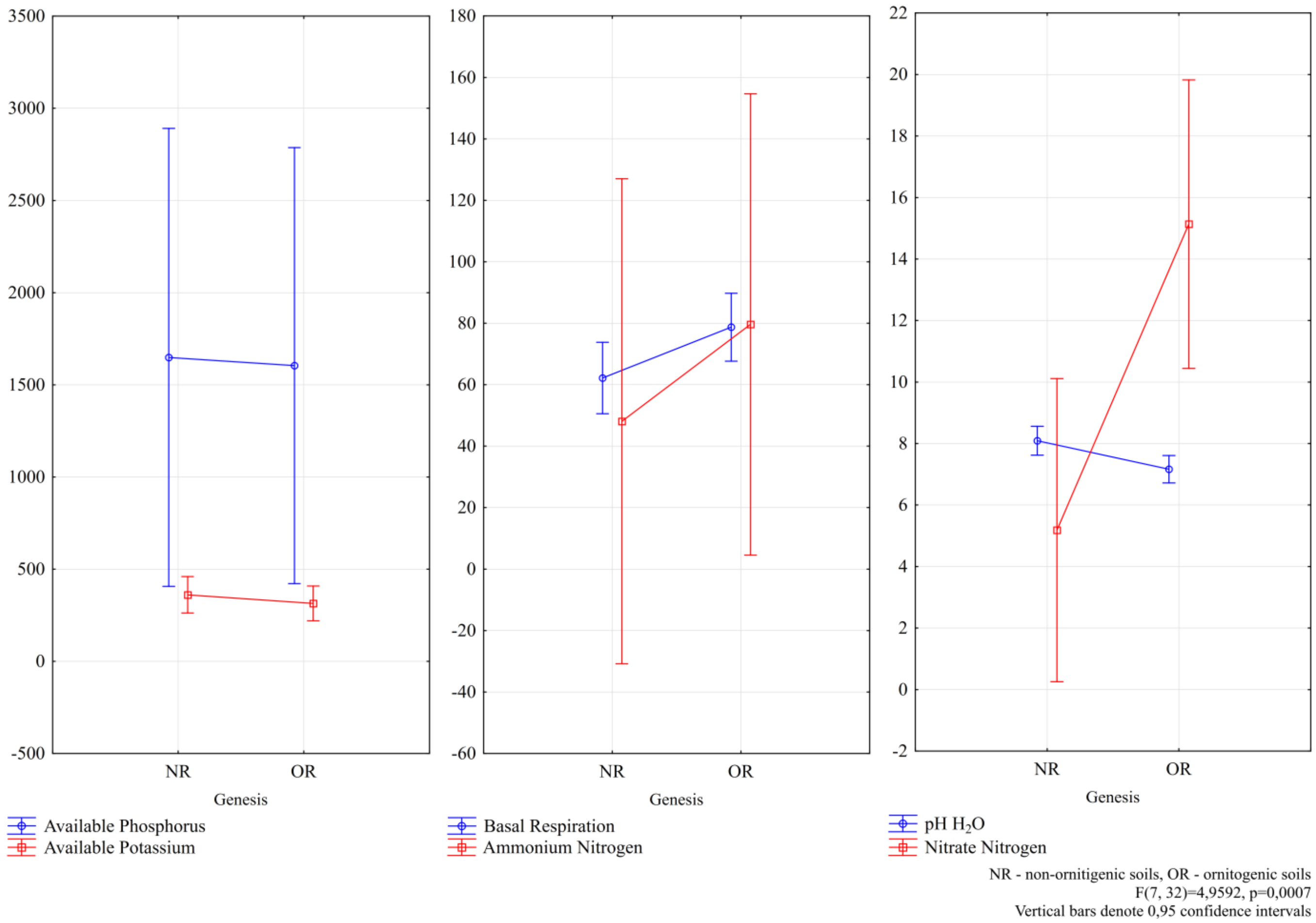


Figure 4. Visualization of variance analysis (ANOVA) of soil properties.

Although to the significant differences between ornithogenic and non-ornithogenic soils obtained by analysis of variance (ANOVA), we cannot clearly distinguish the studied soils by the type of soil forming factor. Even though the samples under study differ in the content of some parameters. The content of available phosphorus and potassium, according to the results of analysis of variance, practically does not change in soils of ornithogenic and non-ornithogenic genesis. As was said above, ornithogenic soil formation contributes to the accumulation of this element in the soil profile. Therefore, we can conclude that the influence of the ornithogenic factor applies equally to all the soils we studied.

The nesting places of Oceanites oceanicus (Wilson's storm petrel) and Pagodroma nivea (Snow petrel) are located mainly on highlands, and due to the settled type of nesting of these species, the organic material of their guano accumulates in the soil profile and then laterally migrates along the slope. The migration of organic matter is possible due to the appearance of some liquid precipitation in the area and the predominantly sandy particle size distribution of soils. Permafrost limits the migration of organic matter into the deeper horizons, which results in the horizontal transfer of organic matter over a wide area. So, the fingerprint of bird activity is evident for all the soils of the studied area, including current ornitogenic soils and geochemically subordinated soils of adjacent areas.

Acknowledgements

Primary support for research was provided by the Arctic and Antarctic Research Institute / Russian Antarctic Expedition’s Subprogram “Study and Research of the Antarctic” of the Federal Target Program “World Ocean”, by the Stock Venture “Polar Marine Geosurvey Expedition” (PMGE) and by the research project of the Komarov Botanical Institute RAS (121021600184-6): “Flora and taxonomy of algae, lichens and bryophytes in Russia and phytogeographically important regions of the world”. The authors would like to express their gratitude to the staff of the Research Park of St. Petersburg University (Research center “Chemical Analysis and Materials Research Centre”). This work was supported by Russian Foundation for Basic Research, project NN 19-05-50107 and 19-54-18003.

References

Abakumov, E., 2018. Content of available forms of nitrogen, potassium and phosphorus in ornithogenic and other soils of the Fildes Peninsula (King George Island, Western Antarctica). *Biological Communications* 63(2): 109-116.

Abakumov, E., Lodygin, E., Gabov, D., Krylenkov, V., 2014. Polycyclic aromatic hydrocarbons content in Antarctica soils as exemplified by the Russian polar stations. *Gigiena i sanitariia* 1: 31-35. [in Russian]

Abakumov, E., Lupachev, A., Andreev, M., Wang, W., Ji, X., 2020a. The influence of brown and south polar skua on the content of plant nutrient in the soils from the Fildes Peninsula (King George Island, West Antarctica). *Chemistry and Ecology* 37(2): 185-199.

Abakumov, E.V., 2011. West Antarctic soils. St. Petersburg University Publishing House. 112p. [in Russian]

Abakumov, E.V., 2014a. Micromorphological features of ornithogenic pedogenesis in Antarctica. *The Russian Journal of Ornithology* 23(1030): 2353-2357. [in Russian]

Abakumov, E.V., 2014b. Zoogenic pedogenesis as the main biogenic soil process in Antarctica. *The Russian Journal of Ornithology* 23(1056): 3095-3107. [in Russian]

Abakumov, E.V., 2019. Ornithogenic soils of Lindsey Island, Pacific Sector of West Antarctica. *The Russian Journal of Ornithology* 28(1748): 1341-1346. [in Russian]

Abakumov, E.V., Andreev, M.P., Lupachev, A.V., Maximova, E.Y., Zhiyanski, M., Ilieva, R., 2019. Role of the South Pole Skua Catharacta maccormicki in the formation of the nutrient regime in the soils of the Fildes Peninsula (West Antarctica). *The Russian Journal of Ornithology* 28(1738): 945-952. [in Russian]

Abakumov, E.V., Parnikoza, I.Y., Vlasov, D.Y., Lupachev, A.V., 2016. Biogenic–abiogenic interaction in Antarctic ornithogenic soils. In: Biogenic—Abiogenic Interactions in Natural and Anthropogenic Systems Frank-Kamenetskaya, O., Panova, E., Vlasov, D. (Eds.). Springer, Berlin, Heidelberg. pp.237-248.

Abakumov, E.V., Zhiyanski, M., Yaneva. R., 2020b. Ornithogenic factor in the formation of tundra vegetation and gray-humus soils on Livingston Island, West Antarctica. *The Russian Journal of Ornithology* 29(1903): 1360-1364. [in Russian]

Alekseev, A., Abakumov, E., 2020. Ornithogenic soils of Maritim Antarctica: genesis, chemical composition, organic matter. *Integrated studies of the natural environment of the Arctic and Antarctic* 1(1): 170-172 [in Russian]

Beyer, L., Pingpank, K., Wriedt, G., Bölter, M., 2000. Soil formation in coastal continental Antarctica (Wilkes Land). *Geoderma* 95: 283-304.

Black, C.A., 1965. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling, Agronomy Monograph 9.1, American Society of Agronomy (ASA), Soil Science Society of America (SSSA), Madison, Wisconsin, USA.

Bockheim, J.G., 2014. Antarctic soil properties and soilscapes. In: Antarctic Terrestrial Microbiology. Cowan, D.A. (Ed.). Springer, Berlin, Heidelberg. pp.293-315.

Bockheim, J.G., 2015 Soil-Forming Factors in Antarctica. In: The Soils of Antarctica. Bockheim, J.G. (Ed.) World Soils Book Series. Springer, Cham. pp.5-20.

Bockheim, J.G., Hall, K.J., 2002. Permafrost, active-layer dynamics and periglacial environments of continental Antarctica: periglacial and permafrost research in the Southern Hemisphere. *South African Journal of Science* 98: 82-90.

Bulavintsev, V., Golovkin, A., Denisova, A., 1993. Snow petrel as a prospective subject of combined ecological monitoring in the Antarctic. *Antarktika. Doklady komissii* 31: 167-178. [in Russian]

Campbell, I. B., Claridge, G., 1987. Antarctica: Soils, weathering processes and environment. Volume 16, 1st Edition. Elsevier. 367p.

Campbell, I.B., Claridge, G.G.C., Campbell, D.I., Balks, M.R., 1998. The Soil Environment of the Mcmurdo Dry Valleys, Antarctica. In: Ecosystem Dynamics in a Polar Desert: the Mcmurdo Dry Valleys, Antarctica. Priscu J.C. (Ed.). American Geophysical Union, Washington, D.C. USA. pp.297-322.

Dolgikh A.V., Mergelov N.S., Abramov A.A., Lupachev A.V., Goryachkin S.V., 2015. Soils of Enderby Land. In: The Soils of Antarctica. In: Bockheim, J.G. (Ed.). World Soils Book Series. Springer, Cham. pp.45-65.

Emslie, S.D., Polito, M.J., Brasso, R., Patterson, W.P, Sun, L., 2014. Ornithogenic soils and the paleoecology of pygoscelid penguins in Antarctica. *Quaternary International* 352: 4-15.

Gibson, J., 2000. The environment of the Bunger Hills. Unpublished report, Australian Antarctic Division, Hobart.

Glazovskaya, M., 1958. Weathering and primary soil formation in Antarctica. *Nauchnyye Doklady Vysshey Shkoly, Geologo-Geograficheskiye nauki* 1: 63-76. [in Russian]

Gorban, V.A., 2015. Ecological soil physics as section of ecological soil science. *Ecology and Noospherology* 26: 96-105.

Goryachkin, S.V., Mergelov, N.S., Targulian, V.O., 2019. Extreme pedology: elements of theory and methodological approaches. *Eurasian Soil Science* 52(1): 1-13.

Heine, J.C, Speir, T.W., 1989. Ornithogenic soils of the Cape Bird Adelie penguin rookeries, Antarctica. *Polar Biology* 10: 89-99.

Hiller, A., Hermichen, W.D., Wand, U., 1995. Radiocarbon-dated subfossil stomach oil deposits from petrel nesting sites: novel paleoenvironmental records from continental Antarctica. *Radiocarbon* 37(2): 171-180.

Hopkins, D.W., Sparrow, A.D., Novis, P.M., Gregorich, E.G., Elberling, B., Greenfield, L.G., 2006. Controls on the distribution of productivity and organic resources in Antarctic Dry Valley soils. *Proceedings of the Royal Society B Biological Sciences* 273(1602): 2687-2695.

Jackson, C.E., Saeger, Jr, C.M., 1935. Use of the pipette method in the fineness test of molding sand. *Part of Journal of Research of the N. Ational Bureau of Standards* 14(1): 59-65.

Janssen, B.H., 1996. Nitrogen mineralization in relation to C:N ratio and decomposability of organic materials. In: Progress in Nitrogen Cycling Studies. Van Cleemput, O., Hofman, G., Vermoesen, A. (Eds.). Developments in Plant and Soil Sciences. vol 68. Springer, Dordrecht. pp. 69-75.

Jenkinson, D.S., Powlson, D.S., 1976. The effects of biocidal treatments on metabolism in soil—V: A method for measuring soil biomass. *Soil Biology and Biochemistry* 8(3): 209-213.

Kachinskiy, N.A., 1958. Mechanical and micro-aggregate composition of soil, methods of its study. Academy of science USSR, Moscow. 193p. [in Russian]

Kostova, I., Apostolova, D., Filcheva, E., Klain, L., Popov, M., 2015. Geochemical composition and properties of Antarctic soil samples from Livingston Island. *Annual of the University of Mining and Geology "St. Ivan Rilski", Part I, Geology and Geophysics* 58: 107-116.

Leishman, M.R., Gibson, J.A.E, Gore, D.B., 2020. Spatial distribution of birds and terrestrial plants in Bunger Hills. *Antarctic Science* 32(2): 153-166.

Lepane, V., Künnis-Beres, K., Kaup, E., Sharma, B., 2018. Dissolved organic matter, nutrients, and bacteria in Antarctic soil core from Schirmacher Oasis. *Journal of Soils and Sediments* 18: 2715-2726.

Lou, Y., Xu, M., Chen, X., He, X., Zhao, K., 2012. Stratification of soil organic C, N and C:N ratio as affected by conservation tillage in two maize fields of China. *Catena* 95: 124-130.

Lupachev, A.V., Abakumov, E.V., 2013. Soils of Marie Byrd Land, West Antarctica. *Eurasian Soil Science* 46: 994–1006.

Mergelov, N.S., 2014. Soils of wet valleys in the larsemann hills and vestfold hills oases (Princess Elizabeth land, east Antarctica). *Eurasian Soil Science* 47: 845-862.

Mergelov, N.S., Goryachkin, S.V., Shorkunov, I.G., Zazovskaya, E.P., Cherkinsky, A. ., 2012. Endolithic pedogenesis and rock varnish on massive crystalline rocks in East Antarctica. *Eurasian Soil Science* 45(10): 901-917.

Miller, A. J., Amundson, R., Burke, I., Yonker, C., 2004. The effect of climate and cultivation on soil organic C and N. *Biogeochemistry* 67: 57-72.

Nikitin, D. A., Semenov, M. V., 2020. Subaqual soils of Antarctica: conditions of formation and perspectives of microbiological research. *Dokuchaev Soil Bulletin* 102: 49-69. [in Russian]

Parnikoza, I., Abakumov, E., Dykyy, I., Pilipenko, D., Shvydun, P., Kozeretska, I., Kunakh, V., 2015. Influence of birds on the spatial distribution of Deschampsia antarctica Desv. on Galindez Island (Argentinean Islands, Coastal Antarctic). *Biological Communications* 1: 78-97. [in Russian]

Parnikoza, I., Dykyy, I., Ivanets, V., Kozeretska, I., Kunakh, V., Rozhok, A., Ochyra, R., Convey, P., 2012. Use of Deschampsia antarctica for nest building by the kelp gull in the Argentine Islands area (maritime Antarctica) and its possible role in plant dispersal. *Polar Biology* 35: 1753-1758.

Saul, D.J., Aislabie, J.M., Brown, C.E., Harris, L., Foght, J.M., 2005. Hydrocarbon contamination changes the bacterial diversity of soil from around Scott Base, Antarctica. *FEMS Microbiology Ecology* 53: 141-155.

Semenov, V.M., 2020. Functions of Carbon in the Mineralization–Immobilization Turnover of Nitrogen in Soil. *Agrochemistry* 6: 78-96. [in Russian]

Simas, F.N.B., Schaefer, C.E.G.R., Filho, M.R.A., Francelino, M.R., Filho, E.I.F., da Costa, L.M., 2008. Genesis, properties and classification of Cryosols from Admiralty Bay, maritime Antarctica. *Geoderma* 144: 116-122.

Simas, F.N.B., Schaefer, C.E.G.R., Melo, V.F., Albuquerque-Filho, M.R., Michel, R.F.M., Pereira, V.V., Gomes, M.R.M., da Costa, L.M., 2007. Ornithogenic cryosols from Maritime Antarctica: Phosphatization as a soil forming process. *Geoderma* 138: 191-203.

Sokolov, I. A., 1993. Theoretical problems of genetic soil science. Science, Novosibirsk. 232p. [in Russian]

Sparks, D.L., Page, A., Helmke, P., Loeppert, R.H., 2020. Methods of soil analysis, Part 3: Chemical methods, John Wiley & Sons. 1390p.

Syroechkovsky, E. E., 2019. The role of animals in the formation of primary soils in the circumpolar region of the globe (the example of Antarctica). *Russian Journal of Ornithology* 28(1809): 3797-3807. [in Russian]

Targul'yan, V.O., 1971. Soil formation and weathering in cold humid areas. Moscow: Nauka. 268p. [in Russian]

Tatur, A., Barczuk, A., 1985. Ornithogenic Phosphates on King George Island in the Maritime Antarctic. In: Antarctic Nutrient Cycles and Food Webs. Siegfried, W.R., Condy, P.R., Laws, R.M. (Eds.). Springer, Berlin, Heidelberg. pp.163-168.

Tatur, A., Keck, A., 1990. Phosphates in ornithogenic soils of the maritime Antarctic. NIPR Symposium on Polar Biology, Proceedings, No.3: pp.133-150.

Tedrow, J.C.F., Ugolini, F.C., 1966. Antarctic Soils. In: Antarctic Soils and Soil Forming Processes, Tedrow, J.C.F. (Ed.). Antarctic Research Series. Volume 8., pp.167-177.

Thomas, G.W., 1996. Soil pH and Soil Acidity. In: Methods of Soil Analysis: Part 3 Chemical Methods, 5.3. Sparks, D., Page, A., Helmke, P., Loeppert, R., Soltanpour, P.N., Tabatabai, M.A., Johnston C.T., Sumner M.E. (Eds.). pp.475-490.

Tucker, N.M., Payne, J.L., Clark, C., Hand, M., Taylor, R.J., Kylander-Clark, A.R., Martin, L., 2017. Proterozoic reworking of Archean (Yilgarn) basement in the Bunger Hills, East Antarctica. *Precambrian Research* 298: 16-38.

U.S. EPA., 1993. Method 350.1: Nitrogen, Ammonia (Colorimetric, Automated Phenate). Revision 2.0. Cincinnati, OH

Ugolini, F.C., 1972. Ornithogenic soils of Antarctica. In: Antarctic Terrestrial Biology. Llano, G.A. (Ed.), American Geophysical Union, Antarctic Research Series, Vol. 20. pp. 181-193.

Ugolini, F.C., Bockheim, J.G., 2008. Antarctic soils and soil formation in a changing environment: A review. *Geoderma* 144(1-2): 1-8.

Vlasov, D.Y., Abakumov, E., Nadporozhskaya, M., Kovsh, N., Krylenkov, V., Lukin, V., Safronova, E., 2005. Lithosols of King George Island, Western Antarctica. *Eurasian Soil Science* 38: 681-687.

Yamashita, T., Flessa, H., John, B., Helfrich, M., Ludwig, B., 2006. Organic matter in density fractions of water-stable aggregates in silty soils: effect of land use. *Soil Biology and Biochemistry* 38(11): 3222-3234.

Zazovskaya, E.P., Fedorov-Davydov, D.G., Alekseeva, T.V., Dergacheva, M.I., 2015. Soils of Queen Maud Land In: The Soils of Antarctica. In: Bockheim, J.G. (Ed.). World Soils Book Series. Springer, Cham. pp.21-24.