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NUTRIENTS AND CATIONS CONTENT IN SOIL SOLUTIONS FROM THE PRESENT AND ABANDONED PENGUIN ROOKERIES (ANTARCTICA, KING GEORGE ISLAND)

ABSTRACT: Penguin rookeries are one of the main sources of nutrients for the poor ecosystems of Antarctica. At the current penguin rookeries, and in their vicinity, nitrogen rich ornithogenic soils are formed. Relict ornithogenic soils created at the abandoned rookeries hundreds or even thousands years ago are rich in phosphates. In the region of maritime Antarctica, water plays an important role in distribution and redistribution of nutrients (surface flows and percolation). Soil decomposition processes result in cations and nutrient release. In nutrients originating from relict ornithogenic soils of the Antarctic tundra, phosphates are the dominating elements; while in nutrients originating from contemporary ornithogenic soils nitrogen (mainly ammonia) is the main ingredient. Mineral soils free of penguin influence contain minute amounts of nutrients. Low pH of soil solutions (<4) causes increase of dissolving of phosphate complexes. Near penguin rookery, pH was lowest (2.73–3.33) and intermediate (2.92–3.77) in relict soils. The values of pH were the highest in soil solutions from mineral soil (5.43–7.33). High concentration of cations (mainly K) in soil solutions from the ornithogenic soils and relict ornithogenic soils, suggest their organic (animal) origin.

KEY WORDS: Antarctica, nutrients, cations, soil solution, fresh waters, relict ornithogenic soil, penguin rookery

1. INTRODUCTION

Ninety percent of King George Island territory (Antarctica) is covered by ice. Remaining parts are rocky shores called "oasis" and nunataks (Korotkevic 1969, Marsz and Rakusa-Suszczewski 1987, Marsz 2001). Climate conditions (King and Turner 1997) and nutrients availability, mainly nitrogen, play an important role in the development of all living world of the unproductive Antarctic ecosystems, ranging from bacteria (Lindeboom 1979, Zdanowski and Węgleński 2001, Bolter *et al.* 2001) to vascular plants (Fabiszewski and Wojtuń 1993, 2000, Olech 1993). In fresh waters (Rheinheimer 1974, Tatur 1983, Juchnowicz-Bierbasz 1999), in the sea environment (Goldberg 1963, Carlucci 1974) and in the soil (Bear 1964, Tedrov and Ugolini 1966, Ugolini 1972, Lindeboom 1979, Tatur and Myrcha 1991), the content of nutrients may vary from place to place and from season to season. Since summer period is relatively short and winter period is long, nutrients supply is related to the presence of mammals and birds.

Nutrients enter to the ecosystem from various sources (Rakusa-Suszczewski 1993a, b). Penguin guano forms ornithogenic soils (Tatur and Myrcha 1984, Tatur 1989), with fresh and leached guano in the surface horizon and aluminium-iron phosphatic clay underneath (Tatur *et al.* 1997). About 3.0 to 6.4 tons of dry guano matter per day is deposited during the breeding season in the penguin Adelie rookeries (Fig. 1) near Arctowski Station (Rakusa-Suszczewski 1980, 1993b, 1995). Intensity of manuring may reach *ca* 10 kg of fresh guano per $1m^2$ of rookeries in the breeding season (Tatur and Myrcha 1991). In the first decade of February after the end of reproduction season and departure of penguins from their rookery, an inflow of organic matter from the sea becomes significantly lower then during the breeding season (Rakusa-Suszczewski 1999).

The relict ornithogenic soils in the area of abandoned rookeries are also important sources of nutrients. (Lindeboom 1979, Myrcha and Tatur 1991, Tatur *et al.* 1993, Beyer *et al.* 1997). The main soil forming process is the biochemical mineralisation of guano and phosphatization of underlying weathered strata (Lindeboom 1979, Pietr *et al.* 1983, Speir and Cowling 1984, Myrcha and Tatur 1991, Tatur *et al.* 1993). During the summer due to the increased temperatures, rain precipitation and thawing of permafrost, the solutions percolate throughout soil, and boundary phase's reactions affect distributions of nutrients.

In addition, seal droppings, macroalgae, (Rakusa-Suszczewski and Zieliński 1993) shells left by the sea on the shores, atmospheric precipitation (Heywood 1968, Davey 1993), anthropogenic factors and also sea spray (Heywood *et al.* 1980) have its share in nutrients supply (Rakusa-Suszczewski 1993c). Grobbelar (1974) detected and described the following order of ionic dominance $Na^+ > Mg^{2+} > Ca^{2+} > K^+ : Cl^- > SO_4^{2-} > HCO_3^-$ which is similar to the one of sea water. Seawater contains high concentration ($mg\ l^{-1}$) of: Na – 10500, Mg –1350, Ca – 400, and K – 380 (Goldberg 1963).

Concentrations of nutrients at the active penguins colonies are too high (Lindeboom 1979, Tatur and Myrcha 1991) and even toxic for the vegetation. Only nitrocoprophilic lichens may accept it (Tatur *et al.* 1997). Released and spread from local centers by the surface waters and soil solutions at various depths nutrients play an extremely important role in enriching unproductive ecosystems of the Antarctic shores.

The aim of the present investigation was the assessment of nutrients and cations concentration in the soil solutions at various depths starting from the surface to the permafrost layer. This has been a continuation of the previous analysis of nutrient concentrations in surface fresh waters in the same area carried out by Juchnowicz-Bierbasz (1999). These habitat data give background of information for the better understanding of colonization by plant communities.

2. STUDY AREA AND METHODS

2.1 STUDY AREA

Investigations were carried out near the Polish Arctowski Antarctic Station at King George Island (62°09' S, 58°28' W) during the austral summer 1999. Region of investigation embraced small hillocks situated south of Arctowski Station at the border of SSSI (Site of Special Scientific Interest) No. 8 within two drainage areas: Ornithologists Creek and Puchalski Creek (Fig. 1) near Jasnorzewski Garden. Typical atmospheric conditions in this area are well described by Marsz and Rakusa-Suszczewski (1987), Rakusa-Suszczewski (1993a, 1993b, 1999) and Rodriquez *et al.* (1996).

Kuhn (1997) proposed several conventional taxonomic soil units for the area under investigation (Table 1). However, Tatur (1989) taking into account high content of ornithogenic phosphates in clay fraction (Table 1, Fig. 1) had differentiated three types of soils: a) the ornithogenic soils (in the area of the actual influence of penguins) that are also present at our work site L8, b) the relict ornithogenic soils (in the area abandoned by penguins hundreds and thousands of years ago – Tatur 1989, sites L3, L5, L6), and c) the mineral soils free of penguin impact (outside and between of the recent and past penguin activity, sites L1, L2, L4, L7).

Lysimeters were placed in the soil (Fig. 1, Table 2) at sites that have been previously studied by Tatur (1989). Selected chemical data related to soil horizon close to depth of the installed lysimeter are presented in Ta-

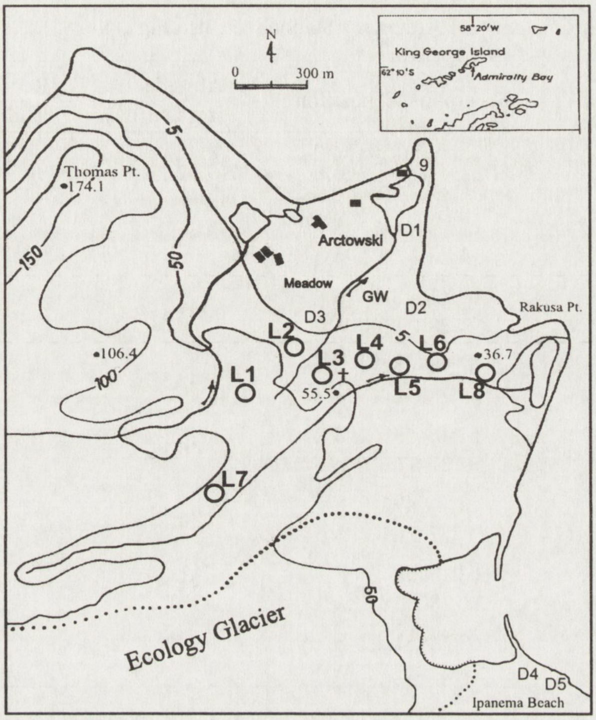

Fig. 1. Location of sampling sites: lysimeters (L1-L8), *Deschampsia antarctica* (D1-D5), and *Colobanthus quitanis* (9) near Arctowski Station (western shore of Admiralty Bay, King George Island, Antarctica). The isolines of attitude of 5, 50, 100 and 150 m, GW – ground water level sampling point, and the edge of Ecology Glacier (dotted lines) are indicated.

Table 1. Description of geographic-morphogenic localization of soil solution stations near Arctowski Station (see also Fig. 1).

Lysimeters stations	Soil type*	Soil Type & Profile No**	Chemical composition of fine soil fraction in relict ornithogenic soils, (% in dry weight)					
			P	Ca	Al	Fe	C	C/N
L1	1	M	–	–	–	–	–	–
L2	2	M (P-19)	5.40	7.41	5.13	4.46	3.94	4.10
L3	4	RO (X)	5.10	0.54	5.98	4.39	3.08	6.10
L4	4	M	–	–	–	–	–	–
L5	4	RO (P-21)	4.80	0.35	3.61	4.41	1.74	1.40
L6	4	RO (P-23)	13.35	0.00	7.96	1.69	1.61	1.50
L7	1	M (P-22)	2.10	2.64	4.40	2.35	2.35	10.20
L8	5	O (P-24)	8.15	0.30	7.66	5.54	2.11	8.80

* according to Kuhn (1998): 1. Gelic Regosls; 2. Humi-gelic Leptosols, Cambisols+Podzosol; 3. Gelic Regosols+Stagnosol; 4. Gelic Umbrisol+Thixotropic Cryosols; 5. Eutri+dystru-gelic Cambisols.
** according to Tatur (1989): O – ornithogenic soil of active rookery, RO – relic ornithogenic soil of abandoned rookery, M – mineral soils outside of penguin influence.

ble 1 and Table 2. During interpretation of the chemical composition of fine fraction of ornithogenic soils free of clastics, it should be kept in mind that content of phosphorus ranged from 10 to 14% in particular ornithogenic phosphates minerals occurring is these soils. This means that soil sample containing 13.35 % of P (sample L5 – Fig. 1, Table 1)

Table 2. Localization of lysimeters near Arctowski Station (see also Fig. 1).

Station	Geographical position	Altitude (m a.s.l.)	Receiving depth of soil solutions (m)
L1	62°09'45.2'' S 58°28'22.3'' W	52.1	0.35
L2	62°09'44.4'' S 58°28'17.9'' W	24.1	0.79
L3	62°09'48.4'' S 58°28'09.0'' W	47.1	0.68
L4	62°09'48.9'' S 58°28'04.4'' W	42.1	0.73
L5	62°09'49.2'' S 58°27'57.6'' W	46.1	0.80
L6	62°09'49.0'' S 58°27'51.1'' W	36.1	0.65
L7	62°09'59.2'' S 58°28'21.8'' W	53.1	0.40
L8	62°09'51.2'' S 58°27'45.1'' W	9.1	0.79

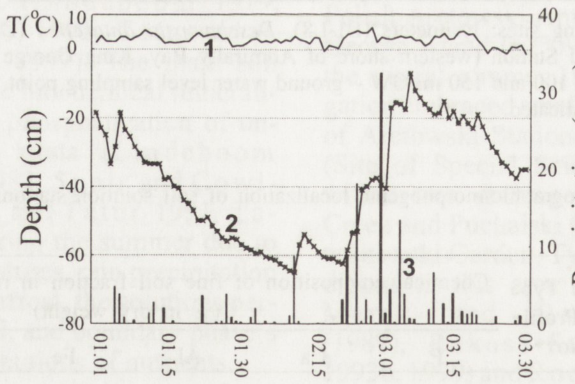

Fig. 2. Variability of: (1) air temperature, (2) level of ground water, and (3) daily sum of atmospheric precipitation, in the summer of 1999

consists of almost pure taranakite. Analyses inform also whether the fine fraction of soil close to depth of installed lysimeter is composed of hydrated Al-Fe phosphates bearing potassium and ammonia ions, or of calcium phosphates typical for guano and relict guano laeyers (Table 1).

Content of cations and CHN were analyzed in samples of *Deschampsia antarctica*, *Colobanthus quitensis*, and in soil, collected at the site of Arctowski Station meadow (Fig. 1).

The average daily air temperature stayed above zero (Fig. 2) from 1 January to 15 March, and dropped below 0 °C in the second part of March. The sum of precipitation at this time was very low, 38. 9 mm. The ground water table (Fig. 2) measured at site GW (Fig. 1) decreased from 9 cm at the end of December, through 19 cm at the beginning of January to 65 cm on 15th March, when water dried almost entirely in nearby streams. This decreasing tendency was kept, despite the fact that each precipitation period (or every rainfall) was accompanied by a visible rise of ground water table (Fig. 2).

2.2 METHODS

Samples of soil solution were collected with lysimeters (Prenart designe) every ten days between 4 January and 15 March 1999 at eight points – (sites ***L*** – Fig. 1, Table 1). Variability of ground water table was measured at one site with piesometer located on flat area of raised beach covered by carpet of mosses (site ***GW***, Fig. 1). Precipitation data (rainfall and snowfall) and air temperature were obtained from meteorological station at Arctowski base (Fig. 1).

Soil solutions were collected in polyethylene bottles, and were analysed after 5 hours stabilisation in dark refrigerator at 5°C. Samples designed to determine cations were conserved after collection with concentrated HNO_3 dissolving 1:1 with water.

Conductivity and total dissolved solids (TDS) were determined with ProfiLine Conductivity Meter LF 197, using TetraCon 325 electrode of WTW. pH was measured with Hanna Instruments HI 9025 using gel Hi 1230B electrode.

Nutrients were analyzed by colorimetric methods using Spekol 1100 (Carl Zeiss):

– $N\text{-}NH_4^+$ – content was determined by the indophenol's method according to Solorzano (1969).

– $N\text{-}NO_2^-$ and $N\text{-}NO_3^-$ – were determined with using Griess reaction (Strickland and Parson 1968).

– $P\text{-}PO_4^{3-}$ – was determined with using the molybdenum blue method (Strickland and Parson 1968).

– $Si\text{-}SiO_4^{4-}$ – was determined according to Grasshoff (1983)

Content of cations (Ca^{2+}, Mg^{2+}, Fe^{3+}, Mg^{2+}, Sr^{2+}) was analyzed on AAS (Atomic Absorption Spectrophotometry), and Na^+, K^+ by the emission flame spectrophotometry according to instruction of Varian Techtron.

Samples of the grass, herbs, and soil were collected near Arctowski Station (Fig. 1) at Arctowski Meadow. *Deschampsia antarctica* (No D4–D5) was also collected from Ipanema beach on the S-side of Ecology glacier. Analyses of cations were done with the ICP-OES technics on a GBC spectrometer (Australia).

Statistical analyses of results were carried out with the "Statistica 5.0 Pl for Windows" program. Cluster analyses, comprising all elements, were accomplished using the complete linkage method (Euclidean distances). Measurements of geographical coordinates of the sampling points were done with the pair of GPS receivers with comparison to the main reference point at the station (cf. Table 1).

3. RESULTS

Concentrations of phosphorus, mineral nitrogen forms as well as the values of conductivity, and TDS in soil solutions were the highest in ornithogenic soils and the lowest in mineral soils located outside of penguins' activity. Concentrations of nutrients, cations, and physico-chemical parameters in solutions from relict ornithogenic soils were in fact usually lower than in ornithogenic soils, however much higher than in mineral soils free of penguin manuring (Table 3, Fig. 1). The ratio between the highest and the lowest nutrient values in investigated solutions was above 1000 for phosphorus and mineral nitrogen forms. Content of silicates was the lowest in solutions from mineral soils free of penguin manuring; here the value were about 15 times lower than the highest ones in solutions from relict ornithogenic soils (Table 3). Soil solutions in the abandoned rookeries are still richer in nutrients (nitrogen and phosphorus) and cations (eg. K^+, Na^+, Ca^{2+}, Mg^{2+}) than mineral soil free of penguins influence (Tables 3, 4). In addition, soil solutions near active penguin rookeries (Fig.1) are richer in mineral nitrogen and cations when compared with solutions from relict ornithogenic soils, mineral soils free of penguins influence (Tables 4, 5), and surface waters (cf. Table 5).

Contents of potassium, calcium, and magnesium are the highest in solutions from ornithogenic and relict ornithogenic soils (Table 4). This is explained by mineralization and incongruent dissolving processes (Cole and Jackson 1950, Tatur and Keck 1990). The contents of sodium at stations L1-L7 are similar which may suggest the influence of aerosols, however, the highest Na^+ concentration was found at station L8 (Table 4), in the area of the present penguin rookeries, thus also it is the result of penguins secretions and excretions. The contents of K^+ are the highest in soil solutions from the area of rookery (L8) and in the areas of relict ornithogenic soils (L3, L5, L6). Mineral soils are poor in potassium (Table 4). Correlation between the contents of potassium and sodium in soil solution, presented by the regression curve of solution of ornithogenic soil (L8) and of solution of relict ornithogenic soil (L3, L5, and L6), showed substantial differences (Fig. 3).

Extremely low pH values were usually noted in solutions from ornithogenic and relict ornithogenic soils, whereas neutral or

Table 3. Concentration of nutrients, pH, conductivity, and total dissolved solids (TDS) at eight stations in soil solutions near Arctowski Station (see also Fig. 1). Mean values and SD (in brackets) are given.

Parameters	Stations							
	L1 n = 1	L2 n = 5	L3 n = 8	L4 n = 1	L5 n = 7	L6 n = 8	L7 n = 8	L8 n = 8
$P\text{-}PO_4^{3-}$	32.34	103.08	157.19	310.93	134.18	1559.87	3.67	1063.43
(mg l^{-1})		(56.35)	(152.24)		(69.22)	(491.27)	(1.18)	(362.02)
$Si\text{-}SiO_4^{4-}$	513.34	646.67	5876.03	3142.30	6715.50	4901.26	580.62	3506.61
(mg l^{-1})		(78.85)	(380.05)		(296.95)	(348.14)	(140.67)	(466.32)
$N\text{-}NO_3^-$	4.60	79.52	85.42	607.56	6.17	40.12	38.79	140.16
(mg l^{-1})		(66.64)	(104.76)		(6.24)	(46.89)	(58.85)	(179.09)
$N\text{-}NH_4^+$	12.99	55.14	55.73	8.48	551.97	349.85	26.14	3326.51
(mg l^{-1})		(71.80)	(34.85)		(180.53)	(125.89)	(23.39)	(1728.91)
$N\text{-}NO_2^-$	1.87	1.22	1.54	3.44	1.97	1.03	0.48	65.40
(mg l^{-1})		(0.77)	(1.63)		(1.48)	(0.99)	(0.38)	(76.16)
pH	6.81	5.58	3.29	3.63	3.35	3.22	6.78	2.97
Conductivity	303.00	268.20	659.50	135.00	868.14	491.25	223.56	1311.75
(μS cm^{-1})		(110.33)	(83.36)		(161.56)	(24.53)	(17.50)	(247.21)
TDS	337.00	297.80	736.00	152.00	967.86	548.25	246.63	1464.50
(mg l^{-1})		(121.18)	(90.00)		(176.68)	(27.75)	(15.46)	(274.47)

Table 4. Concentration of cations (mg l^{-1}) in soil solutions at eight stations near H. Arctowski Station (see also Fig. 1). Mean values and SD (in brackets) are given.

Cations	Stations							
	L1 n = 1	L2 n = 6	L3 n = 8	L4 n = 2	L5 n = 7	L6 n = 8	L7 n = 7	L8 n = 8
Na^+	27.01	27.68	28.87	14.52	20.05	29.93	24.77	48.63
		(2.69)	(1.95)	(2.03)	(2.06)	(1.30)	(1.65)	(8.69)
K^+	1.57	1.30	8.35	1.62	17.55	10.70	0.70	37.01
		(0.22)	(1.13)	(0.57)	(1.67)	(0.46)	(0.15)	(6.03'
Ca^{2+}	21.03	8.03	18.46	11.13	11.58	16.56	9.20	33.16
		(3.22)	(1.41)	(8.90)	(2.14)	(1.35)	(0.91)	(11.14)
Mg^{2+}	6.51	4.36	13.17	1.63	51.86	11.32	5.44	19.99
		(1.15)	(0.95)	(0.61)	(6.86)	(0.94)	(0.56)	(7.28)
Fe^{3+}	0.17	0.45	0.30	0.28	0.32	0.25	0.23	0.27
		(0.51)	(0.15)	(0.11)	(0.11)	(0.05)	(0.05)	(0.07)
Mn^{2+}	0.02	0.03	0.31	0.03	0.89	0.25	0.02	0.67
		(0.01)	(0.02)	(0.01)	(0.19)	(0.03)	(0.004)	(0.20)
Sr^{2+}	0.92	0.96	1.13	0.99	1.12	1.07	0.93	1.39
		(0.05)	(0.07)	(0.04)	(0.07)	(0.05)	(0.05)	(0.12)

Table 5. The variability range (as a min-max interval) of nutrients concentration (mg l^{-1}) and pH from surface water and soil solutions near Arctowski Station (see also Fig. 1).

Parameters	$N\text{-}NH_4^+$	$N\text{-}NO_3^-$	$P\text{-}PO_4^{3-}$	$Si\text{-}SiO_4^{4-}$	$N\text{-}NO_2^-$	pH	Source
Soil solution from:							
– mineral soils free of penguins influence	4.06–177.68	0–97.14	1.42–310.93	473.26–3142.3	0–3.44	5.4–7.3	
– relict ornithogenic soils	24.35–745.9	0–198.06	55.8–1912.7	4576.48–7160.14	0–5.18	2.6–3.8	Present data
– ornithogenic soils	622.2–5088.69	1.69–154.27	275.18–1393.53	2691.1–4297.16	1.11–183.98	2.7–3.3	
Surface water (pounds, creek)	0–4.81	0.03–15.53	0.01–6.14	0.8–181.18	–	5.2–10.6	Juchnowicz--Bierbasz 1999
Surface water flow from penguin rookery	170–7000	0.04–0.05	100–300	–	0.05–0.06	7.4	Tatur, Myrcha 1983
Infiltrated waters from penguin rookery	7–222	36–59	9–40	–	0.05–1.66	4–5.1	

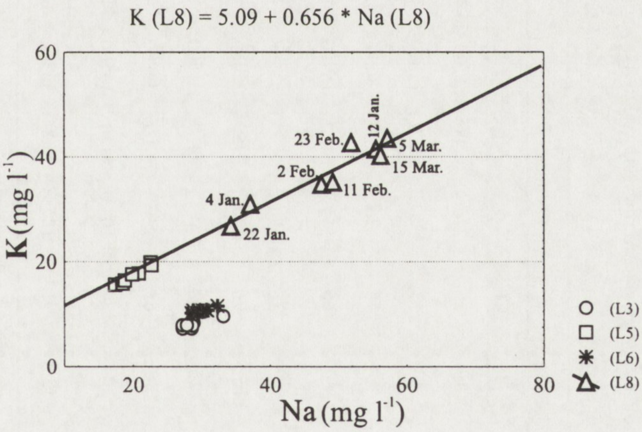

Fig. 3. Linear regression between Na^+ and K^+ for soil solution from ornithogenic soils (L8), and point relationship for soil solution from relict ornithogenic soils with out finding the linear relationship (L3, L5, L6) (Fig. 1)

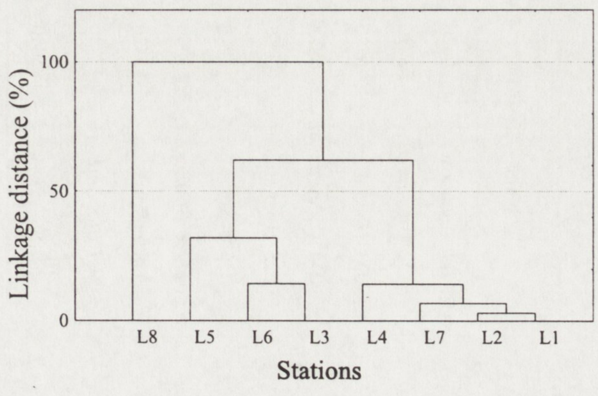

Fig. 4. Cluster analysis of lysimeters sampling points using the complete linkage method. Data from: Table 3 and 4, see Fig. 1; (L8 – ornithogenic soils station), (L3, L5, L6 – relict ornithogenic soils station), and (L1, L2, L4, L7- mineral soil station).

Table 6. Chemical composition of *Deschampsia antarctica* in leaves (D1–D3) and *Colobanthus quitanis* (9) from Arctowski Meadow, and Ipanema beach (D4, D5); soil around the roots of *Deschampsia antarctica* (D6–D8) and *Colobanthus quitanis* (10) from Arctowski Meadow (see also Fig. 1).

Stations	Parameter												C	H	N
	K	Na	Mn	Ni	Cu	Zn	Mg	Al	P	S	Ca	Fe			
D1 (meadow)	9620	5410	176	13	25	215	4700	4790	3960	3150	5170	720	41.3	6.05	2.68
D2 (meadow)	8210	674	366	10	57	39	5870	17820	3580	2550	9220	21780	24.9	3.73	1.52
D3 (meadow)	6720	3660	214	9	56	136	3350	8600	2940	2430	6670	8810	37.9	5.55	2.24
D4 (Ipanema b.)	13200	5690	303	10	66	515	5490	15900	4350	4460	11990	13500	34.71	5.21	3.34
D5 (Ipanema b.)	11120	5320	481	16	91	65	7550	24600	3520	1970	13820	26790	25.68	0.06	1.77
D6& Soil	4970	5350	354	15.5	76	330	8750	22460	4260	2730	12220	32460	17.04	2.61	1.51
D7& Soil	3360	6790	538	15	62	55	7370	31500	2140	900	17540	37600	0.79	0.36	0.06
D8& Soil	3520	7370	536	12	63	59	7700	32800	1820	820	18940	40200	1.28	0.03	0.08
9 *Colobanthus*	8740	8690	223	4	34	108	5110	13100	4360	1850	10200	12360	30.8	4.8	1.7
10 Soil & *Colobanthus*	5040	8290	474	13.5	91	137	9600	36300	6730	1980	23120	37090	5.7	1.1	0.57

Ions concentration in dry weight (mg kg^{-1}), CHN concentration in dry weight (%).

Extremely low pH values were usually noted in solutions from ornithogenic and relict ornithogenic soils, whereas neutral or slightly acid reaction characterized solutions in soils never affected by penguins (Table 3).

Cluster analyses (including: nutrients, pH, Conductivity and TDS, from Table 3, and cations from Table 4) describe similarity among stations, and discriminated three main groups corresponding to ornithogenic, relict ornithogenic, and mineral soils free of penguin influence (Fig. 4).

Nutrients concentration in soil solution from the discussed soil types showed significantly higher values, even of two orders of magnitude, as compared with concentration in surface waters (Table 5).

Contents of cations and CHN in *Deschampsia antarctica* collected at Arctowski Meadow (D1-D3) and Ipanema Beach (D4-D5) are similar – slightly higher at sampling points D4-D5 (Table 6). Chemical composition of *Colobanthus quitensis* (9) is similar to composition of *Deschampsia antarctica* from Arctowski Meadow. With regard to soils from roots layers of *Deschampsia antarctica* (D6-D8) and *Colobanthus quitensis* (10), the concentration of K is substantially lower than in leaves. However, concentration of sodium is similar. Concentration of Fe and Al in soil is almost twice as high than in leaves in both *Deschampsia antarctica* (D6-D8) and *Colobanthus quitensis* (10).

4. DISCUSSION AND CONCLUSION

Coastal geoecosystem of Admiralty Bay is strongly affected by supply of organic matter imported by birds and sea animals from the sea (Rakusa-Suszczewski 1980, 1993a, b, c, 1999). Therefore, the study on the fate of sea animals excreta deposited on land is the principal investigation for the understanding of terrestrial ecology. Soils in the region of Arctowski Station (Kuhn 1997) are typical for the maritime Antarctic climatic zone (Everett 1976, Campbell and Claridge 1987). This includes ornithogenic soils in the current rookeries and relict ornithogenic soils in the area of abandoned nesting sites (Tatur 1989).

Ornithogenic soils of maritime Antarctic are clearly different from analogous soils found in the Antarctic Continent (Syroechkovsky 1959, Tedrov and Ugolini 1966, Ugolini 1972, Tatur *et al.* 1997). Typical mineral feature of ornithogenic soils in maritime Antarctic is the common occurrence of the relatively stable (durable) aluminum-iron phosphates containing potassium and ammonia ions. They are formed in these areas due to abundance of liquid water and in soils derived from rocks susceptible to phosphatization processes (Tatur and Keck 1990).

Moreover, the phosphate minerals are still present in the relict ornithogenic soils abandoned by penguins many years ago and even thousands of years ago (Tatur 1989, Tatur and Myrcha 1993). Solubility equilibrium constants of these complex phosphates (Cole and Jackson 1950) and analyzes of water extracts from relict ornithogenic soils (Tatur and Myrcha 1991) suggest that they may supply nutrients and cations to coastal geoecosystem even in the sites of rookeries abandoned many years ago (Tatur 1989).

The present study performed *in situ* gives proofs (Tables 4 and 5) that the assumption of Tatur (1989), Tatur and Myrcha (1991, 1993), and Tatur *et al.* (1997) was correct.

Particularly evident is the difference in ammonia and nitrite forms of nitrogen, documenting intense microbiological process of fresh guano decomposition. Differences in the contents of nitrates between both sites (recent and relict rookeries) are less clear. This proves that in both, recent and relict (released from old phosphates) rookeries, ammonia ions are the subject of nitrification processes that were documented also in earlier studies (Tatur and Myrcha 1983, Tatur and Myrcha 1984, Tatur and Barczuk 1985, Pietr 1984, Rankin and Wolff 2000). However, content of ortho-phosphates and silicates may be even a little higher in soils of abandoned rookeries than in soils near active rookeries.

Weather conditions like heavy rainfalls also influence the chemical composition of soil solution (high concentration of nutrients and cations) that is flowing from active penguin rookeries, and in consequence manuring the land ecosystem. The guano deposits may be washed down at such period. Such solution contains high level of organic suspension, pH >7.4, and $NH_4^+ >> NO_3^-$ (Tatur and Myrcha 1983, 1984). Opposite situation occurs when water percolates through the soils (pH < 7.4, $NH_4^+ << NO_3^-$). The soil solution from relict ornithogenic soils is strongly acid (pH 3–4) without organic suspension, and the excess of NH_4^+ to NO_3^- is similar to that in solution from ornithogenic soils. Such low pH value were observed by Cameron and Benoit (1970). They noted pH ranging from 3.0 to 3.8, and explained this by volcanic origin of soils, similar to that near Arctowski Station.

High content of nutrients that have been lasting for many years in soil solutions from rookeries abandoned long time ago, results probably from the typical in such cases incongruent dissolution of complex soil phosphates (taranakite, leucophosphite, minyulite). During this process the cations (K^+ and NH_4^+), and partially phosphorus enrich solution, but the remaining elements form a solid product: highly hydrated, basic - amorphous aluminum phosphate (Tables 3 and 4). That mineral phase, which is much less soluble, forms a cover over the complex phosphates protecting them against further rapid dissolving (Tatur and Keck 1990, Tatur and Myrcha 1991). This process may explain the delayed dissolving of soil phosphates in the area of abandoned rookeries.

In the colony area the positive correlation between the content of PO_4^{3-}, NH_4^+, K^+ in the cloacal fluid and the body weight of Adelie penguins chicks (Janes 1997) suggest, that with the growth of chicks there might occur a periodical increase of these compounds in excrements. Varying concentrations of the cations of K^+, Na^+, Ca^{2+} and Mg^{2+} found in solutions from different soils are helpful in determining the origin of soils (ornithogenic, relict ornithogenic and mineral). Dispersion of Na^+/K^+ (Fig. 3) in soil solution from ornithogenic soil (L8) changed in time and could be dependent on the influence of fresh penguins guano (manuring and mineralization processes), and precipitation (runoff of surface solution with organic suspension from penguin colony). Compared with cations concentration in soil solution from relict ornithogenic soils, they show stability over longer times.

Leaching from relict ornithogenic soils and penguin rookery causes the highest concentration of nutrients and cations in soil solutions; this may in turn influences the content of cations in *Deschampsia antarctica*. This corroborates with the findings of Tatur *et al.* (1997).

The Arctowski Meadow where *Deschampsia antarctica* and *Colobanthus quitensis* grow (Zarzycki 1993, Barcikowski and Luścińska 2001), has been manured by soil solution from abandoned and active penguin rookeries, and also by sea aerosols. Quantities of nutrients should be moderate – not too high (active penguin rookeries), and not too low (mineral soils – free of penguin influence), (Tatur and Myrcha 1983, 1984, Tatur 1989, Myrcha *et al.* 1985, Tatur *et al.* 1997). This has been confirmed by our results. Average contents of carbon (35.9%) and of nitrogen (2.0%, points 1–5) of *Deschampsia antarctica* were comparable with the results of Fabiszewski and Wojtuń (2000) who found the values for carbon and nitrogen 36.5% and 2.7%, respectively – (C/N – 13.7). Average concentrations of cations (Ca^{2+} – 2840, Mg^{2+} – 1500, K^+ – 4900, Na^+ – 1060 (mg kg^{-1})) given by Fabiszewski and Wojtuń (2000), are similar to our results with the exception of potassium, the content of which is about twice lower compared to our result (Table 6). Also the contents of P, K, Mg, Cu, Mn, Zn are greater in the Antarctic grasses, than in the Arctic (Dziadowiec and Gugnacka-Fiedor 1992, Jóźwik 2000). Differences between contents of cations in soil and leaves of *Deschampsia antarctica* from Arctowski Meadow and Ipanema Beach could be explained by the fact that Arctowski Meadow is frequently flooded and washed by thaw water from surrounding hills. This protects the soil from over manuring, securing an optimal nutrients inflow. Ipanema Beach is the territory under the influence of heavy seawater splashes as aerosols, and high contents of penguin guano solutions. Thaw waters do not wash it. Therefore, water in liquid state, plays an important role in maritime Antarctic ecosystem as nutrients carrier between the soil and the vegetation, and as the nutrients' dissolvent.

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5. SUMMARY

The analyses were performed on soil solutions form ornithogenic soils, relict ornithogenic soils and mineral soils free of penguin influence (Table 1, Fig. 1).

Our analyses of soil solutions showed high concentration of nutrients in both ornithogenic and relict ornithogenic soils (Tables 3 and 5). Ornithogenic soils and relict ornithogenic soils contained large amounts of stable (durable) aluminum-iron phosphates formed in the process of phosphatization (Table 2). Additionally, high concentration of K^+ and Ca^{2+} in soil solutions from ornithogenic and relict ornithogenic soils (Table 4, Fig. 3) emphasize origin of nutrients and cations from these soils (Fig. 4). In mineral soils free of penguins influence, substantially low concentrations of nutrients and cations were observed.

In the stream of nutrients derived from relict ornithogenic soils reaching Antarctic tundra, phosphates are the most frequently detected, while in ornithogenic soils it is nitrogen (mainly ammonia).

The weather conditions (temperature, precipitation) have a remarkable influence on the amount of nutrients and cations delivered to the ecosystem by soil solution from abandoned and present penguin rookeries (Fig. 2). During heavy rains or rapid thaws, surface run-off of guano suspension enters directly the Admiralty Bay. Within the rookeries, surface run-off of guano suspension showed pH > 7.4 and an excess of ammonia nitrogen over nitrate ($NH_4^+ >> NO_3^-$). However, after infiltration of water into the ornithogenic and relict ornithogenic soil profiles, pH of soil solutions was strongly acidic (ca. 3.4), whereas in mineral soils free of penguin influences, it was slightly acidic or neutral (Table 3). In the case of percolating water, this relation was reversed: pH < 7.4, $NH_4 << NO_3$ (Table 4).

The Arctowski Meadow where *Deschampsia antarctica* and *Colobanthus quitensis* grow, has been manured by soil solution from abandoned and active penguin rookeries, and also by sea aerosols. Quantities of nutrients should be moderate – not too high (active penguin rookeries), and not too low (mineral soils – free of penguin influence), (Table 6).

Adding up, soil solution from ornithogenic and relict ornithogenic areas, is a very important source of nutrients and cations for flora of the costal zone of maritime Antarctic.

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