Organic carbon stocks in permafrost-affected soils from Admiralty Bay, Antarctica

F. N. B. Simas,[1] C. E. G. R. Schaefer,[2] E. S. Mendonça,[2] I. R. Silva,[2] R. M. Santana,[2] and A. S. S. Ribeiro[2]

[1]Centro Universitário de Caratinga-UNEC, Mestrado em Meio Ambiente e Sustentabilidade, Caratinga- MG, Brazil (fsimass@yahoo.com.br)
[2]Departamento de Solos – Universidade Federal de Viçosa, Av. PH Rolfs, s/n, Viçosa, Minas Gerais Brazil

Abstract -Recent works show that organic matter accumulation in some soils from coastal Antarctica is higher than previously expected. The objective of the present work was to estimate the organic C stocks for soils from maritime Antarctica. Cryosols from subpolar desert landscapes presented the lowest organic C stocks. Ornithogenic soils are the most important C reservoirs in terrestrial ecosystems in this part of Antarctica. Although these soils correspond to only 2.5 % of the ice-free areas at Admiralty Bay, they contain approximately 20 % of the estimated C stock. Most of the organic C in the studied soils is stored in the active layer but in some cases the C is also stored in the permafrost.

Citation: Simas, F.N.B., C.E.G.R. Schaefer, E.S. Mendonça, I.R. Silva, R.M. Santana, A.S.S. Ribeiro (2007), Organic carbon stocks in permafrost-affected soils from Admiralty Bay, Antarctica, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A.K. Cooper and C.R.Raymond et al., USGS Open-File Report 2007-1047, Short Research Paper 076, 4 p.; doi: 10.3133/of2007-1047.srp076

Introduction

Permafrost-affected soils (Gelisols - SSSA, 2006 or Cryosols – ISSS, 1998) from maritime Antarctica are different from those from other parts of Antarctica (Campbell and Claridge, 1987; Blume et al., 2004). Warmer temperatures and higher water availability result in deeper active layers and favor primary production and mineral weathering. Mosses and lichens form large communities at some sites and a close relationship between faunal terrestrial activity and vegetation establishment is observed (Myrcha et al., 1985; Tatur et al., 1997). Intense bird activity, especially by penguins, results in the formation of ornithogenic soils (Ugolini, 1972; Tatur, 1989; Simas et al., 2007). According to Ugolini (1972), guano accumulation in penguin rookeries represents the most abundant source of organic matter in the Antarctic terrestrial ecosystem. At ornithogenic sites, the occurrence of two higher plants (*Deschampsia antarctica* Desv. (Poaceae) and *Colobanthus quitensis* (Kunth) Bartl. (Caryophyllaceae)) increases organic matter accumulation in the soil. Recent studies show relatively high levels of organic matter in some soils from coastal Antarctica (Beyer et al., 1995; Beyer et al., 2004).

Soil organic carbon stocks are regulated by primary production and SOM decomposition rates. The study of organic C pools is essential for a better understanding of Antarctic terrestrial ecosystems in the current climate change scenario. According to Bockheim et al. (1999), C stocks in near-surface permafrost may be of global significance at high latitudes and should be inventoried. Increasing temperatures lead to permafrost melting which may increase mineralization rates as verified for Arctic tundra soils (Ping et al., 1997). The objective of the present work was to investigate the distribution of SOM in ice-free areas of Admiralty Bay, King George Island, and estimate the organic carbon stocks for representative soils from maritime Antarctica.

Material and methods

King George Island is part of the South Shetlands Archipelago, maritime Antarctic (Figure 1). The total ice free area in Admiralty Bay is approximately 3000 ha. We have grouped the soils from Admiralty Bay in: i) Basaltic/andesitic soils; ii) acid sulfate soils; (iii) weakly ornithogenic soils; iv) ornithogenic soils. Chemical, physical and mineralogical characteristics of each soil group are presented in Simas et al. (2006, 2007). In order to study in more detail soils organic C, we subdivided the basaltic/andesitic soil group in: a) subpolar desert soils with very sparse vegetation and; b) soils covered by mosses and lichens. The ornithogenic soils were also separated in: a) soils from active rookeries; b) soils from abandoned rookeries and; c) moss peats. Each of these soils represents a particular environment with distinct patterns of primary production and pedological characteristics which influence C sequestration in soils.

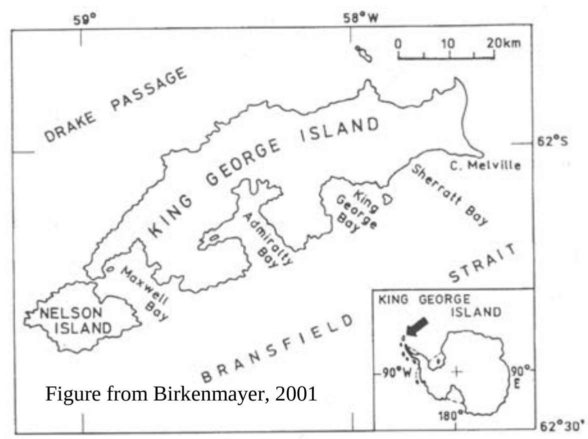

Figure 1. Location of Admiralty Bay, King George Island.

Fifty-six (56) pedons were described, sampled and analyzed. The soils were classified according to the U.S. Soil Taxonomy (SSSA, 2006) with adaptations (Simas et al., 2007). Active layer depth varied from 45 to 65 cm in the end of the summers of 2003 to 2005.

We opted to analyze soils < 0.5 mm fraction, because soils of maritime Antarctica have a very high amount of rock fragments in the fine earth fraction (< 2 mm). Total organic C was determined by wet combustion (Yeomans and Breemner, 1988). The content of > 0.5 mm particles in the soils, including cobbles and pebbles (> 2 mm) was obtained gravimetrically. C stocks were estimated according to Batjes (1996):

Cst = (TOC)(BD)*(LT)*(1 - % fragments>0.5 mm)*, where: Cst = carbon stock (Mg/m^2); TOC = total organic carbon (gC/gsoil), BD = bulk density (Mg/m^3) and LT = layer thickness (m). C stocks were calculated for 0-30 cm and 0-100 cm depths. When the pedon was shallower than 100 cm, the value of the deepest layer was repeated until the 100 cm depth was reached.

Results and Discussion

Total organic carbon content (TOC)

The levels of soil TOC (Table 1) and total N (not presented) were higher for sites with more developed vegetation communities. At the uppermost parts of the landscape, desert valleys with well drained soils have the lowest organic C content and negligible total N. These soils represent over 90 % of the ice-free areas from Admiralty Bay. Continuous moss communities colonize soils along melt water channels and TOC levels are slightly higher but not statistically different from the desert soils ($p < 0.05$ - Student's *t* test).

Organic C and total N levels are highest for soils from abandoned penguin rookeries (Table 1). Several studies have dealt with such soils (Ugolini, 1972; Tatur, 1989; Tatur et al., 1997; Michel et al., 2006), but very few (Simas et al., 2007) have discussed the impact of flying birds (skuas, giant petrels and sea gulls). Flying birds prey on penguins and nest around the rookeries, expanding the ornithogenic influence. Our data indicate that this incipient ornithogenic influence can enhance vegetation development and lead to considerably high organic C values (13.1±11.0 g/kg). Although these soils with *weak* ornithogenic influence have a smaller geographic expression, the TOC levels were similar and sometimes higher than soils with *strong* ornithogenic character (Table 1). The moss peat had the highest C levels at depth. Soils covered exclusively by cryptogamic species show an abrupt decrease in TOC values at depth. On the other hand, soils supporting flowering plants (pedons K20, K23, A3 and A5) have a more gradual decrease and normally maintain high TOC values at depth (Table 1). At ornithogenic sites, thick moss carpets were formed. At well-drained sites, moss communities were gradually overgrown by the higher plants *Deschampsia Antarctica* and *Colobanthus quitensis. D. Antarctica* forms continuous grass fields with a dense network of well-developed root systems in the A horizon. Roots are common in the deeper soil layers resulting in the higher TOC values with depth. It has been shown that root-derived organic C has in average a 2.4 times higher residence time in soils than shoot-derived organic C and that the contribution of the root system to stabilizing soil organic matter is greater than that of the aerial parts (Rasse et al., 2005).

Table 1 – Total organic C (TOC), bulk density and content of > 0.5 mm particles for the studied soils

Depth (cm)	TOC (g/kg)	BD (g/cm^3)	>0.5 mm particles (%)
Basaltic/andesitic - Subpolar desert			
Pedon K16 -Typic Haploturbel			
0-70	1.0	1.3	55.9
Pedon A10 - Typic Psamoturbel			
0-70	1.0	1.3	82.9
Basaltic/andesitic - Cryptogamic vegetation			
Pedon K13 - Typic Haploturbel			
0-10	41.0	0.5	97.1
10-20	5.0	1.2	97.1
20-60	2.0	1.3	92.8
Pedon K21 - Lithic Haploturbel			
0-10	9.0	1.1	98.1
10-50	2.0	1.3	94.7
Acid sulfate soil			
Pedon K24 - Sulphuric Haploturbel			
0-10	5.0	1.2	60.0
10-20	2.0	1.3	25.2
20-60	1.0	1.3	46.3
Weak ornithogenic influence			
Pedon K20 - Typic Umbriturbel			
0-10	65.0	0.3	95.7
10-20	19.0	0.8	95.9
20-50	7.0	1.2	88.4
Pedon K23 - Typic Umbriturbel			
0-10	36.0	0.5	95.1
10-30	21.0	0.8	90.3
30-40	12.0	1.0	96.0
40-50	7.0	1.2	95.7
50-60	3.0	1.3	97.9
Ornithogenic - Active penguin rookery			
Pedon A5 - Ornithogenic Haploturbel			
10-20	26.0	0.7	94.4
20-30	7.0	1.2	97.5
Ornithogenic - Abandoned penguin rookery			
Pedon A3 - Ornithogenic Psammoturbel			
0-10	15.0	0.9	99.0
10-20	8.0	1.1	99.4
20-70	13.0	1.0	97.1
Pedon A6 – Ornithogenic Umbriturbel			
0-10	24.0	0.7	95.9
10-20	20.0	0.8	96.5
30-50	13.0	1.0	93.0
Ornithogenic - Moss peat			
Pedon A7 - Ornithogenic Fibristel			
0-10	44.0	0.4	97.1
10-20	35.0	0.6	96.4
20-30	22.0	0.8	96.4
30-70	31.0	0.6	85.7
70-80	21.0	0.8	96.4

Organic C stocks

The estimated organic C stocks for representative pedons of each soil group are presented in Table 2. The total stocks ranged from 0.3 to 7.0 kg/m^2 for the mineral soils and reached 11.1 kg/m^2 for the organic soil (pedon A7). Michel (2006) reported similar ranges (0.1 to 9.0 kg/m^2) for soils from the vicinities of Llano Point, in Admiralty Bay. These values are also within the ranges presented by Beyer et al. (2004) for soils near Casey Station (0.3 to 8.2 kg/m^2 for mineral soils, and 5.2 to 45.6 kg/m^2 for Gelic Histosols). Compared to the Artic region, the estimated C stocks are low in relation to the range reported by Bockheim et al. (1999) for tundra soils (2.5 to 75.2 kg/m^2) and much lower than those reported by Ping et al. (1997) for coastal marsh and forest soils (69.2 kg/m^2 and 78.7 kg/m^2, respectively). Tarnocai et al. (2003), considering a soil depth of 100 cm, reported C stocks ranging from 17.0 to 80.3 kg/m^2 for Turbic Cryosols from Eurasia. These values are much higher than that obtained in the present study for the same soil depth (0.48 – 9,09 kg/m^2). For Turbic Cryosols from North America (Tarnocai et al., 2003), this range is wider (0.3 to 136.6 kg/m^2) and the soils from Admiralty Bay fall above its lower value.

As expected, subpolar desert soils had the lowest C stocks in Admiralty Bay (Table 2). The estimated C stocks for pedons K16 and A10 were lower than the global mean reported by Batjes (1996) for world soils (0.8 to 40.6 kg/m^2 for 30 cm, and 3.1 kg/m^2 to 77.6 kg/m^2 for 100 cm). Therefore, these ahumic cryosols from Antarctica are probably amongst the soils with the lowest C content on the planet. The organic C stocks estimated for soils under cryptogamic vegetation (Table 2) are also low in relation to most soil classes in the world (Batjes, 1996) and similar to those estimated for some soils from eastern Antarctica (Beyer et al., 2004).

Sites under ornithogenic influence have much higher organic C stocks. At the active penguin rookery (pedon A5), C stock is lower because no vegetation occurs at these sites due to intense trampling by penguins. The activity of skuas results in a considerable increase in C stocks as observed for pedons K20 and K23 (Table 2), being comparable to that estimated for soils from penguin rookeries and mineral soils from coastal eastern Antarctica (Beyer et al., 2004). Despite their limited geographic expression, nesting sites of skuas, giant petrels and sea-gulls are important C sinks in Antarctica. Until now, the impacts of these birds in terrestrial ecosystem had received almost no scientific interest.

The Ornithogenic Fibristel had the highest C stock (13.55 kg/m^2), considering a 100 cm depth (Table 2). This value is much lower than the global mean reported by Batjes (1996) for Histosols (72 – 125 kg/m^2) and by Tarnocai et al. (2003) for organic Cryosols from the northern circumpolar area (19.5 to 133.7 kg/m^2). However, it falls within the range reported by Beyer et al. (2004) for Histels from coastal eastern Antarctica (5.2 to 45.6 kg/m^2). In pedon A7, more than 60 % of the organic C is stored below 30 cm from the soil surface, indicating that most of the organic C is located in the permafrost. Therefore, similarly to some Arctic soils, climate change may convert organic soils in Antarctica from carbon sinks to sources.

Besides the organic C levels, which are notably increased by the ornithogenic influence, variations in the coarse particle content in soils also determines total C stock estimates. In the present study, both pedons from the Psammoturbel great group (pedons A10 and A3) presented the lowest C stocks when compared to Haploturbels from similar environments (Table 2).

Table 2. Estimated C stocks for the selected pedons at different depths.

Soil	Depth	C stock	0-100 (cm)	0-30 (cm)
	cm	kg/m^2		
Basaltic/andesitic - Subpolar desert				
K16 – Typic Haploturbel	70	1.11	1.59	0.47
A10 – Typic Psamoturbel	70	0.33	0.48	0.14
Basaltic/andesitic - Cryptogamic vegetation				
K13 – Typic Haploturbel	60	2.00	2.42	1.70
K21 – Typic Haploturbel	50	0.64	0.96	0.51
Acid sulfate soil				
K24 – Sulfuric Haploturbel	60	2.30	2.97	1.79
Weak ornithogenic influence				
K20 – Typic Umbriturbel	50	4.65	7.79	3.40
K23 – Typic Umbriturbel	60	7.04	7.50	4.67
Ornithogenic - Active penguin rookery				
A5 – Ornit. Haploturbel	30	2.38	5.52	2.38
Ornithogenic - Abandoned penguin rookery				
A3 – Ornit. Psammoturbel	70	1.17	1.64	0.55
A6 – Ornit. Umbriturbel	50	4.53	9.09	3.63
Ornithogenic - Moss peat				
A7 – Ornit. Fibristel	70	11.06	13.55	4.15

Due to the coarse texture, the Psammoturbel from the abandoned penguin rookery (pedon A6) had lower C stocks than the acid sulfate soil (pedon K24) despite the much higher TOC levels in the < 0.5mm fraction for A6. The acid sulfate soil had the lowest amount of particles > 0.5 mm and, therefore, presented a quite high C stock considering the relatively low organic C content. This is also valid for some basaltic/andesitic soils such as pedon K16.

For most of the studied pedons (K13, K21, K24, K20, K23, A5, A3 and A6), a greater part of the organic C stock is stored in the first 30 cm. However, in the case of deeper pedons (K16, A10, A3 and A7) or when the depth of 100 cm is considered for all pedons, most of the organic C is stored below 30 cm. In the case of ornithogenic soils (e.g., pedons A3 and A7), this is can be attributed to the high organic C values at depth (Simas et al., 2007) due to the intense cryoturbation which incorporates soil organic matter deep in the profile. For pedons K16 and A10, the higher C stock at depth is a result of the sum of the stocks in each layer down to 100 cm.

Ornithogenic soils comprise approximately 76.4 ha, which corresponds to approximately 2.5 % of the ice free areas of Admiralty Bay (Francelino, 2004; Michel, 2005; Santana, 2006). Considering an average C stock of 3.2kg/m^2 for the first 30 cm of soil for the ornithogenic sites, the TOC stored in these soils would be around 2.4 x 10^3 Mg. Considering a mean C stock of 0.3 kg of C/m^2 and a total area of 2900 ha, the TOC stock estimated for the non-ornithogenic soils is approximately 8.7 x 10^3 Mg. According to these estimates, the TOC stored in the first 30 cm of the soils in Admiralty Bay is around 11.1 x 10^3 Mg. Although ornithogenic soils represent only 2.5 % of the ice-free areas, they contain approximately 22 % of the total organic carbon mass stored in the first 30 cm of soils in ice-free areas of Admiralty Bay.

Summary

1. Ice-free areas of Admiralty Bay are formed mainly by subpolar desert soils with very low C stocks. The establishment of cryptogamic communities occurs at humid sites but soil C stocks are still lower than that found for most soils from high latitudes.
2. Despite their reduced geographic expression, ornithogenic soils are the most important compartment of immobilized C in ice-free areas of Admiralty Bay. The presence of higher plants at these sites, with well developed root systems, coincides with higher organic C levels with depth. TOC levels were highest for poorly drained sites where moss peats have formed and over 60 % of the organic C stock is stored in the permafrost layer. Eventual global warming and permafrost degradation may change these sites from C sinks to sources.
3. Sites under the influence of flying birds may have total organic C levels and stocks comparable to those observed in areas under much stronger influence by penguins and should be studied in more detail.

Acknowledgements. We acknowledge Professors Jim Bockheim and Megan Balks for reviewing the first version of this paper and co-editor Sandra Passchier for her valuable help. We also thank the Brazilian Council of Science and Technology (CNPq) and the Brazilian Antarctic Program (PROANTAR) for financing the project (CNPq 550368, Cryosols of Maritime Antarctica).

References

Batjes, N. H. (1996), Total Carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47, 151-163.

Beyer, L., C. Sorge, H. P. Blume, and H. R. Schulten (1995), Soil organic matter composition and transformation in Gelic Histosols of coastal Continental Antarctica. Soil Biology and Biochemistry, 27, 1279-1288.

Beyer, L., K. Pingpank, M. Bolter, and R. D. Seppelt (2004), Soil Organic Matter Storage in Cold Soils of Coastal Eastern Antarctica (Casey Station, Wilkes Land), in Cryosols - Permafrost Affected Soils, edited by J. Kimble, pp. 509-525, Springer-Verlag, Berlin.

Birkenmajer, K. (2001), Retreat of the Ecology Glacier, Admiralty Bay, King George Island (South Shetland Islands, West Antarctica), 1956-2001, Bulletin of the Polish Academy of Sciences, Earth Sciences, 50, 16-29.

Blume, H. P., J. Chen, E. Kalk, and D. Kuhn (2004), Mineralogy and Weathering of Antarctic Cryosols, in Cryosols - Permafrost Affected Soils, edited by J. Kimble, pp. 415-426, Springer-Verlag, Berlin.

Bockheim, J. G., D. A. Walker, and L. R. Everett (1998), Soil carbon distribution in nonacidic and acidic tundra of arctic Alaska, Russian Acad. Sci., Pushchino, Russia.

Bockheim, J. G., L. R. Everett, K. M. Hinkel, F. E. Nelson, and J. Brown (1999), Soil Organic Carbon Storage and Distribution in Arctic Tundra, Barrow, Alaska. Soil Sci. Soc. Am. J., 63, 934–940.

Campbell, I. B., and G. G. C. Claridge (1987), Antarctica: soils, weathering processes and environment, 368 p., Elsevier-Amsterdam.

Francelino, M. R. (2004), Utilização de fotografias aéreas não convencionais para o mapeamento geoambiental das áreas livres de gelo da Península Keller, Ilha Rei George, Antártica Marítima. D.Sc. Thesis, 134 p., Universidade Federal de Viçosa, MG, Brasil (in portuguese).

Santana, R. M. (2006), Ortorestituição de fotografias aéreas não convencionais como subsídio ao mapeamento geoambiental da Baía do Almirantado, Antártica Marítima, D.Sc. Thesis, 120 p., Universidade Federal de Viçosa, MG, Brasil (in Portuguese).

Michel, R. F. M. (2005), Solos Criogênicos e Ornitogênicos na Área de Entorno da Ponta Llano, Antártica Marítima, M.Sc. Thesis, 80 p., Universidade Federal de Viçosa, MG., Brasil (in Portuguese).

Michel, R. F. M., C.E.G.R. Schaefer, L. Dias, F.N.B. Simas, V. Benites, and E.S. Mendonça (2006), Ornithogenic Gelisols (Cryosols) from maritime Antarctica: pedogenesis, vegetation and carbon studies, Soil Sci. Soc. Am. Journal, 70, 1370-1376.

Myrcha, A, S. J. Pietr, and A. Tatur (1985), The Role of Pygoscelid Penguin Rockeries in Nutrient Cycles at Admiralty Bay, King George Island, in Antarctic Nutrient Cycles and Food Webs, edited by W. R. Siegfried, P. R. Condy and R. M. Laws, pp. 156-163, Springer-Verlag, Berlin.

Oechel, W. C., and W. D. Billings (1992). Effects of global change on the Carbon balance of Arctic plants and ecosystems, in Arctic Ecosystems in a Changing Climate, edited by F. S. Chapin III, R. L. Jefferies, J. F. Reynolds, G. R. Shaver, and J. Svoboda, pp. 139–168, Academic Press, Inc.

Ping, C. L., G. J. Michaelson, and J. M. Kimble (1997), Carbon storage along a latitudinal transect in Alaska. Nutrient Cycling in Agroecosystems, 49, 235–242.

Rasse, D. P., C. Rumpel, and M. F. Dignac (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilization. Plant and Soil, 269, 341-346.

Simas, F. N. B., C. E. G. R. Schaefer, V. F. Melo, M. B. B. Guerra, M. Saunders, and R. J. Gilkes (2006), Clay-sized minerals in permafrost-affected soils (Cryosols) from King George Island, Antarctica, Clays and Clay Minerals, 54, 723-738.

Simas, F.N.B., C.E.G.R. Schaefer, V. F. Melo, M. R. Albuquerque-Filho, R. F. Michel, V. V. Pereira and M. R. M. Gomes (2007). Ornithogenic Cryosols from maritime Antarctica: phosphatization as a soil forming process, Geoderma, 138, 191-207.

SSSA, Soil Survey Staff (2006), Keys to Soil Taxonomy, 10th ed.. USDA-NRCS. Washington, D.C.

Tarnocai, C., J. Kimble, G. Broll (2003). Determining carbon stocks in Cryosols using the Northern and Mid Latitudes Soil Database, in Permafrost, edited by Phillips, Springman, and Areson, pp.1129-1134, Swets and Zeitlinger, Lisse.

Tatur, A. (1989), Ornithogenic soils of the maritime Antarctic. Pol. Polar Res., 4, 481-532.

Tatur, A., A. Myrcha, and J. Niegodzisz (1997). Formation of abandoned penguin rookery ecosystems in the maritime Antarctic. Polar Biol., 17, 405-417.

Ugolini F. C. (1972), Ornithogenic soils of Antarctica, in Antarctic Terrestrial Biology, edited by G.A. Llano, pp. 181-193, Am. Geophys. Union Antarct. Res. Ser.

Yeomans, J. C and J. M. Bremner (1988). A rapid and precise method for routine determination of organic carbon in soil. Commun. Soil Sci. Plant Anal., 19, 1467-147.