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Spatial variability models of CO_2 emissions from soils colonized by grass (*Deschampsia antarctica*) and moss (*Sanionia uncinata*) in Admiralty Bay, King George Island

EDUARDO DE SÁ MENDONÇA[1,4], NEWTON LA SCALA, JR[2]*, ALAN RODRIGO PANOSSO[2], FELIPE N.B. SIMAS[3] and CARLOS E.G.R. SCHAEFER[3]

[1]*Department of Plant Production, Federal University of Espírito Santo, 29500-000, Alegre, ES, Brazil*
[2]*FCAV, Univ Estadual Paulista, Via de Acesso Prof. Paulo Donato Castellane s/n, 14884-900, Jaboticabal, SP, Brazil*
[3]*Soil Science Department, Federal University of Viçosa, Av. PH Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brazil*
[4]*Advisor at the Soil and Plant Nutrition Post-graduation Program, Federal University of Viçosa, 36570-000, Viçosa, Minas Gerais, Brazil*
**corresponding author: lascala@fcav.unesp.br*

Abstract: Soil CO_2 emission is an important part of the terrestrial carbon cycling and is influenced by several factors, such as type and distribution of vegetation. In this work we evaluated the spatial variability of soil CO_2 emission in terrestrial ecosystems of maritime Antarctica, under two contrasting vegetation covers: 1) grass areas of *Deschampsia antarctica* Desv., and 2) moss carpets of *Sanionia uncinata* (Hedw.) Loeske. Highest mean emission was obtained for the *Deschampsia* ($4.13\ \mu mol\ m^{-2}\ s^{-1}$) developed on organic-rich soil with a strong penguin influence. The overall results indicate that soil temperature is not directly related to the spatial pattern of soil CO_2 emission at the sites studied. Emission adjusted models were Gaussian and exponential with ranges varying from 1.3 to 2.8 m, depending on the studied site and vegetation cover.

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Introduction

The maritime Antarctic has recently experienced the highest temperature increases in Antarctica (Vaughan *et al*. 2001, Quayle *et al*. 2002, Steig *et al*. 2009), accompanied by regional changes in rainfall (Turner *et al*. 1997). These changes are expected to affect soil CO_2 emissions as soil temperature and moisture are related to microbial activity and soil carbon mineralization (Davidson & Janssens 2006). Recent studies have claimed that temporal and spatial changes in soil temperature and moisture, in different environments, would result in significant modifications in soil respiration (Martin & Bolstad 2009). However, little attention has been paid to the spatial variability as affected by the size and distribution of plant communities (Smith 1994, Grobe *et al*. 1997), although experiments have shown that a two years warming period was enough to significantly alter plant growth (Day *et al*. 1999). The increase in plant biomass would not just enhance root respiration but also the spatial distribution of soil CO_2 emission (Luo *et al*. 2001).

In the maritime Antarctic a marked expansion of higher plant (*Deschampsia antarctica* Desv. and *Colobanthus quitensis* (Kunth) Bartl.) populations has recently been observed at some sites (Parnikoza *et al*. 2009) with similar changes observed for moss vegetation, which is the dominant community on ice free areas of this region (Convey 2006). Since soil CO_2 emission is also driven by plant respiration, which in its turn is affected by photosynthetic activity (Kuzyakov & Gavrichkova 2010), it is expected that changes in vegetation distribution and composition, in addition to changes in temperature and moisture regimes, would affect CO_2 emissions, particularly its spatial variability. Additional information on ecological and physiological aspects of plants and their sensitivity to changing soil temperature is also demanded, especially in West Antarctica (Convey *et al*. 2009).

Soil CO_2 emission is an important aspect of terrestrial carbon cycling and can be influenced by several factors that vary in time and space. In vegetated soils, emissions are driven by microbial decomposition of soil carbon (C) and plant roots respiration (Tang & Baldocchi 2005, Kuzyakov & Gavrichkova 2010). Therefore, when addressing the spatial variability of soil CO_2 emission, a grid should be installed to allow the recognition of the variability range. In this regard, CO_2 emission measurements from bare soils have shown that a significant part of the variability in heterotrophic respiration occurs at a sub-metre scale (La Scala *et al*. 2000). Similar studies in vegetated soils have found a variability range from a few to a hundred metres, depending on vegetation and litter distribution (Rochette *et al*. 1991, Fang *et al*. 1998). Most variability is certainly due to the influence of root respiration on the emission process. Studies have shown increases in soil respiration

Table I. Location, soil and vegetation type in the studied sites.

Site	Location (UTM fuse 21)	Soil	Vegetation
I	0427091 E, 3116260 N	Leptic Thimorphic Cryosol	*Sanionia*/*Deschampsia*
II	0427107 E, 3115861 N	Leptic Thimorphic Cryosol	*Sanionia*
III	0423593 E, 3106696 N	Ornithogenic Histosol	*Deschampsia*

closer to the stems or crops in forest and agricultural fields, respectively (Tang & Baldocchi 2005).

Soil CO_2 emission is also driven by soil temperature, especially in colder regions (Hopkins *et al*. 2006, Park & Day 2007), but studies have concentrated mostly on the role of temperature on the temporal variability of emission, with little attention to spatial variability. Such emphasis has been certainly due to the fact that West Antarctica has warmed about 0.1°C per decade, especially in winter and spring (Steig *et al*. 2009).

When soil respiration is being considered, soil water content is often considered an important factor, especially in sub-Antarctic islands where during most of the thawing period soil water content is close to field capacity (Smith 2003). Studies conducted at the Antarctic Dry Valleys have shown that soil CO_2 efflux is driven primarily by physical variables such as soil temperature and moisture (Ball *et al*. 2009).

Elsewhere, other properties related to organic matter content and quality and soil aeration, have been cited as also controlling spatial variability patterns of CO_2 emissions (Fang *et al*. 1998, La Scala *et al*. 2000, Xu & Qi 2001, Schwendenmann *et al*. 2003, Epron *et al*. 2004). Most of the studies of CO_2 emission in soils at high latitudes and their response to climate change have been developed in Arctic tundra ecosystems (Lloyd 2001, Oberbauer *et al*. 2007) with little attention given to the maritime Antarctic.

The objective of the present study was to compare soil CO_2 emissions between two typical vegetation communities of maritime Antarctica and determine the spatial variability models of soil CO_2 emission and soil temperature.

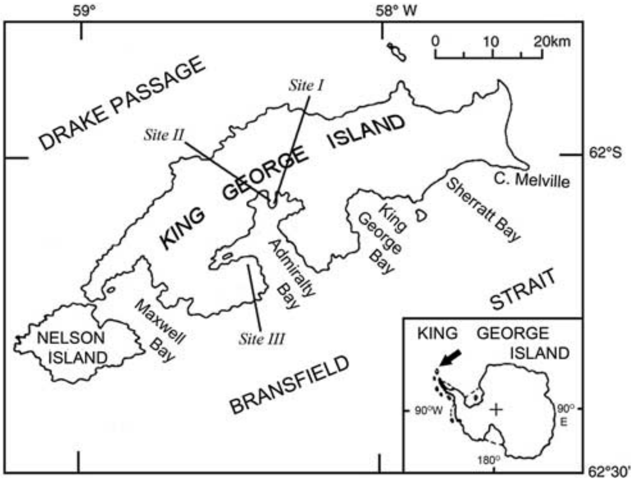

Fig. 1. Map showing the studied sites located in Peninsula Keller (sites I and II) and in Arctowski (site III), King George Island.

Materials and methods

The study was conducted at three different locations in ice-free areas along the shores of Admiralty Bay, King George Island, South Shetland Islands, in soils previously studied by Michel *et al*. (2006) and Simas *et al*. (2007a) (Table I, Fig. 1). The soil at sites I and II is a Leptic Thiomorphic Cryosol (according to the WRB system), with acid pH, low organic C levels and is highly weathered by Antarctic standards (Simas *et al*. 2007a). Both sites I and II are located in the vicinity of the Brazilian Comandante Ferraz Station, on the portion of Keller Peninsula which is affected by sulphide-rock mineralization. Soil at site III is a Turbi-Histic Cryosol, formerly affected by penguin guano, being located close to the Polish Henryk Arctowski Station. Several works highlight this soil type as the main organic C sinks of Antarctic terrestrial areas (Ugolini 1972, Simas *et al*. 2007a, 2007b).

At site I two different communities, one composed of a continuous moss carpet of *Sanionia uncinata*, and another composed of grass tufts of *Deschampsia antarctica*, occur side by side. This was considered a reference site to compare CO_2 emissions from these two communities in a similar pedogeomorphological setting.

A pure moss carpet of *Sanionia uncinata* (Hedw.) Loeske covers site II and a continuous stand of *Deschampsia antarctica* occurs at site III. These sites were used mainly to compare the spatial variability of CO_2 emissions.

Measurements of soil CO_2 emissions were conducted in March 2009, in the morning at site I and in the afternoon at sites II and III, on days of optimum solar radiation and exposure, with low wind speed. Emissions were measured in a 60-point regularly spaced grid previously installed at each site. The grid size was 3.3 x 1.2 m with a minimum distance of 0.3 m between grid points. At site I, measurements were obtained for 30 points for each of the two vegetation types.

CO_2 emissions were measured using a portable LI-8100 analyser (LiCor, EUA) coupled to a dynamic chamber (LI-8100-102), known as survey chamber, having 10 cm diameter placed on PVC soil collars inserted in the soil before the experiment. Occasionally the 10 cm diameter collars were placed in areas with less extensive vegetation with some bare soil, due to the natural heterogeneity of the vegetation. Soil temperature for the 0–10 cm layer was measured in all studied points.

Emission determination at each grid point was based on a single measurement lasting 1.5 min. The measurement of CO_2 concentration inside the chamber was performed every three seconds. At the end of each single measurement, an interpolation was computed to calculate the emission value for each point. The whole 60 points grid took around 2 h to measure.

The spatial variability was analysed by using descriptive statistics and the adjustment of the semivariogram models to the soil CO_2 emission and soil temperature data. The semivariance was estimated by:

$$\hat{\gamma}(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[z(x_i) - z(x_i + h)\right]^2,$$

where: $\hat{\gamma}(h)$ is the semivariance at a separation distance h, N(h) is the number of the pairs of points separated by h, $z(x_i)$ is the property value at point x_i and $z(x_i + h)$ is the property value in the point $x_i + h$.

The semivariogram graph can have a completely random or a systematic behaviour, which can be described by theoretical models (spherical, Gaussian, exponential, etc.) (Isaaks & Srivatava 1989). In this case, the semi-variance value increases with separation of the points (h distance) until a distance that the sill ($C_0 + C_1$) is kept constant. The distance where this stabilization occurs is called range distance (a). The pure nugget effect (C_0) is the value where the adjusted theoretical model crosses the y axis.

The model adjusted to the semivariogram was used in order to generate the so-called "kriging map" by interpolation techniques, estimating the studied property at non-sampled places. This is a process that is related to estimations based on the property values of the closest neighbours, and with the knowledge of the adjusted theoretical semivariogram models (Webster & Oliver 1990).

Only isotropic semivariograms were considered in this study. Experimental semivariograms were adjusted for the following theoretical models:

a) exponential, $\hat{\gamma}(h) = C_0 + C_1\{1 - \exp[-3(h/a)]\}$, $h > 0$,

b) spherical, $\hat{\gamma}(h) = C_0 + C_1[3/2(h/a) - 1/2(h/a)^3]$, $0 \leq h \leq a$, and $\hat{\gamma}(h) = C_0 + C_1$, $h > a$,

c) Gaussian, $\hat{\gamma}(h) = C_0 + C_1\{1 - \exp[-3(h/a)^2]\}$, $h > 0$.

The cross-validation technique was used to verify the reliability of the mathematical model. This technique consisted of testing the semivariogram model validity by kriging at each sampled location using all neighbouring samples, and then comparing estimates with observed values. The model chosen was the one that adjusted the observed and estimated values closer, i.e. the one that produced a linear regression equation between the observed and estimated values that was closer to the bisectrix (Isaaks & Srivastava 1989). In general, results showed a mean error close to zero indicating no systematic bias, and an average ratio between the square error of prediction and the estimation variance close to the unity, showing a good fit of the semivariogram model to the dataset. After having generated all the semivariogram models, values for each soil variable at the observation points were used for prediction values at unknown points using the ordinary kriging interpolation method.

Table II. Descriptive statistics of soil CO_2 emission (μmol m^{-2} s^{-1}) and soil temperature (°C) in the studied sites.

Site*	Mean	s.e.	SD	Minimum	Maximum	CV(%)
Soil CO_2 emission						
I-D	1.49	0.17	0.92	0.00	3.13	62
I-S	1.32	0.11	0.59	0.00	2.61	45
II	1.06	0.06	0.46	0.00	2.90	43
III	4.13	0.28	2.13	0.00	11.81	52
Soil temperature (°C)						
I	4.9	0.2	1.2	3.2	8.5	25
II	7.3	0.1	0.7	6.1	9.0	09
III	6.9	0.1	0.8	5.9	9.0	12

* I-D = *Deschampsia antarctica,* I-S = *Sanionia uncinata* ($n = 30$), for the rest $n = 60$, s.e. = standard error, SD = standard deviation, CV = coefficient of variation.

Descriptive statistics of CO_2 emissions as well as graph elaborations were obtained using the Origin 6.0 software (OriginLab, Inc, Northampton, MA, USA). Spatial variability models were derived using GS+ software (Gamma Design Software, LLC, Plainwell, MI, USA, 1998) and kriging maps obtained with Surfer software (Golden Software Inc, Golden, CO, USA, 1995).

Results and discussion

At reference site I, mean soil CO_2 emission was higher for *Deschampsia* (1.49 μmol $m^{-2}s^{-1}$, CV = 61.6%) than for *Sanionia* (1.32 μmol $m^{-2}s^{-1}$, CV = 45.04%), but did not differ according to Student's *t*-test ($P = 0.39$). The mean temperature for the whole site was 4.9°C (Table II). This result indicates that at the same soil, geomorphological and climatic conditions, soils with *Deschampsia antarctica* emit similar amounts of CO_2 to those with *Sanionia uncinata*. This is in disagreement with other studies which report that photosynthesis of *Deschampsia* is better adapted than *Sanionia uncianata* to the levels of solar irradiance and UV radiation typical of Antarctica (Montiel *et al.* 1999).

When comparing mean emissions between *Sanionia uncinata* at sites I and II, the latter presented a lower mean value (1.06 μmol m^{-2} s^{-1}, Student's *t*-test, $P < 0.01$) (Table II). Both sites are on acid-sulphate soils, with similar chemical and mineralogical characteristics, described in detail by Simas *et al.* (2006, 2007a). Therefore, site-specific conditions, which were not evaluated in the present study, such as soil water content, slope and aspect, which may affect photosynthesis of plants and the activity of soil microorganisms, may explain this difference. Also, the different periods of the day in which measurements were made (morning at site I and afternoon at

Table III. Mean ± standard error (s.e.), Coefficient of Variation (CV), models and semivariogram estimated parameters obtained for the soil CO_2 emission (μmol m^{-2}s^{-1}) and soil temperature (°C) for the studied sites.

Site	Mean ± s.e.	CV	Model	C_0	$C_0 + C_1$	a (m)	r^2	DSD
Soil CO_2 emission								
I	1.41 ± 0.10	55	Exponential	0.1041	0.3242	1.3	0.95	0.32
II	1.06 ± 0.06	43	Gaussian	0.0588	0.1111	2.3	0.96	0.53
III	4.13 ± 0.28	52	Gaussian	0.1031	0.2872	2.8	0.98	0.36
Soil temperature								
I	4.94 ± 0.16	25	Gaussian	0.1840	2.3620	3.0	0.96	0.08
II	7.29 ± 0.09	9	Gaussian	0.2064	0.5168	3.0	0.93	0.40
III	6.92 ± 0.10	12	Spherical	0.0200	0.2266	1.5	0.90	0.08

$n = 60$, a = range distance, DSD = degree of spatial dependence = $C_0/(C_0 + C_1)$, strong for values smaller than 0.25, moderate when between 0.25 and 0.75, and week above 0.75 (Cambardella *et al.* 1994).

site II) might have influenced the results. It is noteworthy that site II had a higher mean temperature (7.3°C) than site I (4.9°C), but lower mean CO_2 emission (Table II), suggesting that soil temperature is not the main factor controlling these emissions.

A much higher difference was obtained when comparing CO_2 emissions from *Deschampsia* at sites I and III. At the latter, the mean emission value was almost three times higher than at site I (Student's *t*-test, $P < 0.01$) (Table II). We attribute this large difference mainly to contrasting soil characteristics between the sites. At site III, *Deschampsia* grows on a thick histic epipedon in an environment strongly influenced by a penguin rookery situated upslope. Soil water enriched in P and nitrogen which drain from the penguin rookery interact with the underlying soil resulting in the phosphatization of the mineral substrate, enhancing vegetation development (Simas *et al.* 2007a, 2007b).

Although we have not measured autotrophic and heterotrophic respiration separately, the enhanced nutrient levels at site III are expected to favour both plant photosynthesis rates and microbial mineralization of soil organic matter, when compared to site I. Photosynthesis supplies organic substances that are respired by roots and microorganisms and therefore should be considered as one of the main drivers of carbon fluxes (Kuzyakov & Gavrichkova 2010).

When comparing sites II and III, the latter emitted on average almost four times more CO_2 than site II (Table II). This large difference is also attributed to the specific soil characteristics at site III, which favour emission mechanisms.

Site III presented the highest emission, but not the highest mean temperature (Table II). This indicates that despite the fact that temperature is known as an important factor in predicting the temporal variability of Antarctic soil CO_2 emission (Hopkins *et al.* 2006, Park & Day 2007), it does not explain the spatial variability, at least at vegetated sites.

The emissions for sites I, II and, especially, site III can be considered high, being comparable to those registered in a similar study with soils affected by seabirds and seals on sub-Antarctic Marion Island (Smith 2005). These values are much higher than those reported for soils from the Dry Valleys of Antarctica (Ball *et al.* 2009) and Arctic tundra ecosystems (Lloyd 2001, Oberbauer *et al.* 2007). The carbon-rich Histic Cryosol under *Deschampsia* (site III) showed the highest maximum emission (11.81 μmol m^{-2} s^{-1}). Minimum emissions, close to zero, were registered at some points, for all studied sites (Table II). These low emissions were usually from grid points with less dense vegetation, emphasizing the direct effect of vegetation to CO_2 emission, mostly due to plant roots respiration, as observed by Welker *et al.* (2000) in the Arctic tundra.

The large difference between maximum and minimum emissions results in high coefficients of variation (CV) values, which is typical of soil CO_2 emission patterns. High variability of soil CO_2 emission was observed by Fang *et al.* (1998) and

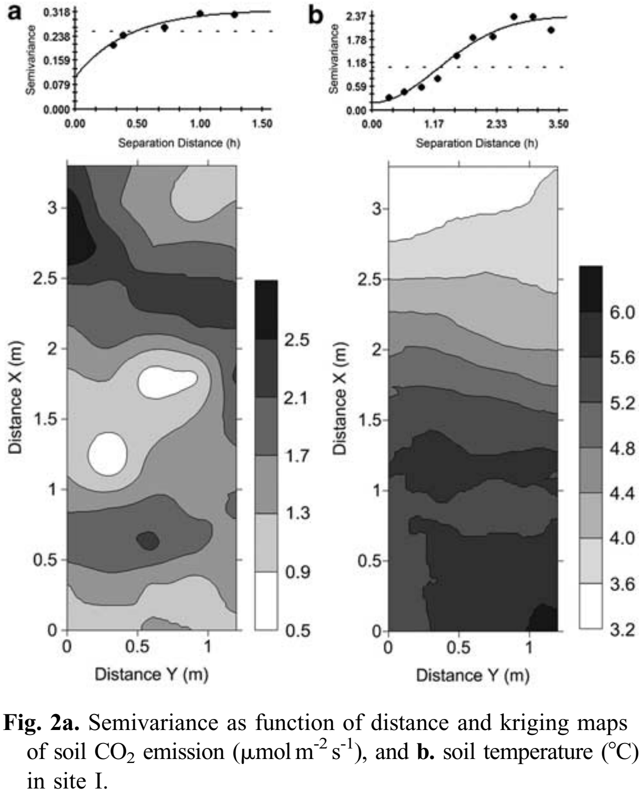

Fig. 2a. Semivariance as function of distance and kriging maps of soil CO_2 emission (μmol m^{-2} s^{-1}), and **b.** soil temperature (°C) in site I.

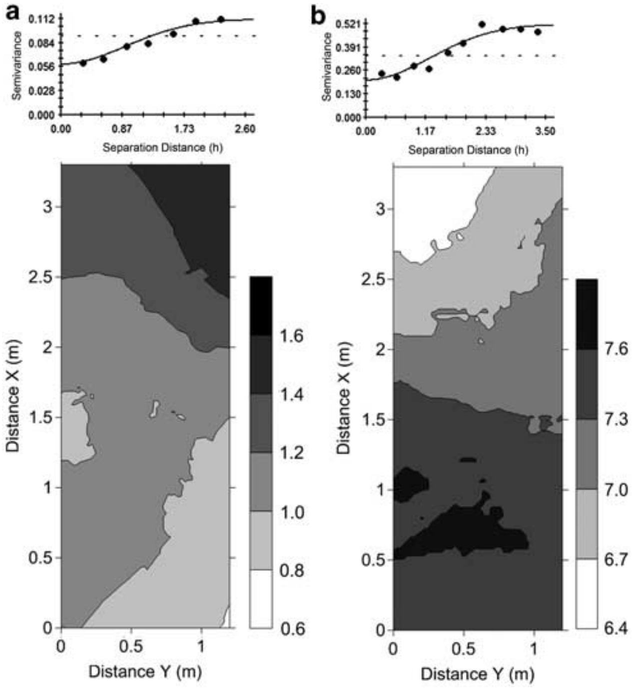

Fig. 3a. Semivariance as function of distance and kriging maps of soil CO_2 emission ($\mu mol\, m^{-2}\, s^{-1}$), and **b.** soil temperature (°C) in site II.

Rayment & Jarvis (2000), who reported CV values ranging from 55 to 87%, justifying the use of geostatistics to model spatial dependence of CO_2 emissions.

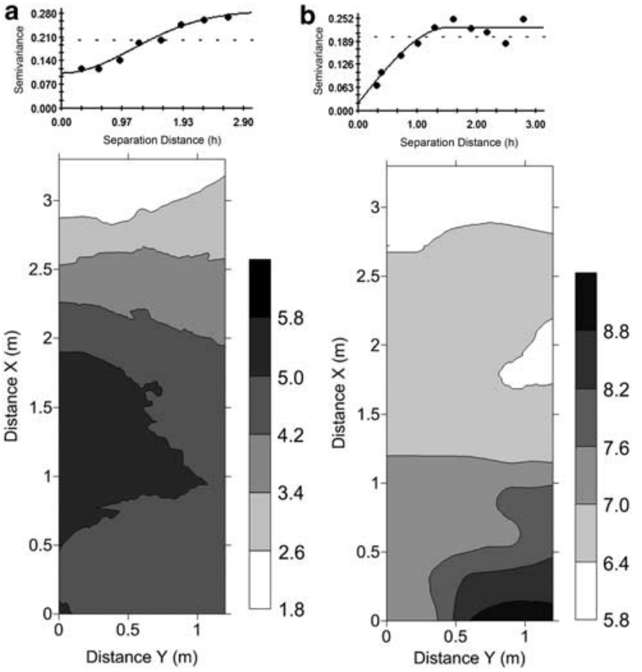

Fig. 4a. Semivariance as function of distance and kriging maps of soil CO_2 emission ($\mu mol\, m^{-2}\, s^{-1}$), and **b.** soil temperature (°C) in site III.

Before geostatistics analysis was conducted a logarithmic transform was applied to the soil CO_2 emission data, making it possible to adjust the semivariogram models to the experimental semivariograms. The semivariogram parameters adjusted to soil CO_2 emission and soil temperature in all sites are presented in Table III. Care must be taken with interpretation of site I because calculations were made using 30 point of each vegetation type and therefore do not represent the behaviour of a specific community but a mixture of the two different organisms.

Fitted models were Gaussian for emission at sites II and III and exponential in site I (Table III or graphs in Figs 2–4). All the adjusted models had high determination coefficients ($r^2 > 0.90$). Most of the spatial variability models observed for soil CO_2 emission have been described by either spherical or exponential models (Dasselaar *et al*. 1998, Stoyan *et al*. 2000, La Scala *et al*. 2000, Ishizuka *et al*. 2005, Tedeschi *et al*. 2006, Kosugi *et al*. 2007, Ohashi & Gyokusen 2007, Konda *et al*. 2008). On the other hand, according to Isaaks & Srivastava (1989) Gaussian and spherical models can best describe phenomena having high continuity, without large changes at local scale, while exponential models best adjust to more erratic data.

The local scale of the spatial variability is represented by C_0 parameter that was similar for all sites, with a slightly lower value for site II. The spatial variability structure, expressed by the C_1 parameter, indicates similar values for all studied sites, with site II again having a slightly lower trend. The most used parameter in this case is the so-called degree of spatial dependence (DSD, Table III) expressed by $C_0/C_0 + C_1$ ratio (Cambardella *et al*. 1994). In the present work, the DSD was moderate ($0.25 < \text{DSD} < 0.75$) for emissions in all the studied sites. Similar studies have presented DSD for soil CO_2 emission, varying mostly from weak to moderate (La Scala *et al*. 2000, Stoyan *et al*. 2000, Ishizuka *et al*. 2005), but DSD has been shown to vary seasonally or even with the grid size (working scale) (Ohashi & Gyokusen 2007, Kosugi *et al*. 2007, Konda *et al*. 2008). With regard to temperature, the DSD was strong ($\text{DSD} < 0.25$) for sites I and III and moderate in site II.

Range value is an important aspect in the spatial variability model as it indicates the spatial dependence among neighbour's points. CO_2 emission ranges were 1.3, 2.2 and 2.8 m for sites I, II, III, respectively. According to Trangmar *et al*. (1985) range values can tell us about the heterogeneity of data when considering its spatial distribution in a grid. Higher range values observed in site II and III suggest higher homogeneity of emission values, implying that more points would be necessary at site I to have an appropriate emission measurement. This was expected since site I data represents two different vegetation covers. *Deschampsia antarctica* had an overall higher mean emission (1.49 $\mu mol\, m^{-2}\, s^{-1}$) compared with remaining points under mosses (1.32 $\mu mol\, m^{-2}\, s^{-1}$). This feature is consistent with the CO_2 emission map (Fig. 2a), illustrating higher emission rates on *Deschampsia antarctica*.

Soil temperature ranged from 1.5°C in site III to 3°C in sites I and II, suggesting there is no coupling with the spatial variability structure (models and ranges) of soil CO_2 emission. This is consistent with fact that soil temperature has little direct effect on the spatial variability of soil CO_2 emission at each site. This can also be observed by relating CO_2 emission to temperature in each site: when the 60 point measurements are linearly related, no significant result is found ($P > 0.10$).

Kriging maps of soil CO_2 emission and soil temperature at each site are presented in Figs 2–4, together with the semivariograms and adjusted models. There is clearly more continuity of isolines for emission maps from sites II and III, compared to site I. This can also be observed in soil temperature maps, suggesting that vegetation cover may also control the continuity or discontinuity of both properties in space. Therefore distribution of soil CO_2 emission and soil temperature did not appear to be related to soil type, but was associated with the vegetation distribution at each site.

Conclusions

1. In the present study, organic-rich soils with high nutrient availability covered with *Deschampsia* were the main sources of CO_2 emission from the terrestrial ecosystem back to the atmosphere. Apart from being the major organic C sinks in Antarctic terrestrial ecosystems, soils influenced by penguin manure, once colonized with *Deschampsia,* are potentially the highest terrestrial C source to the atmosphere.
2. Our data also suggests that under similar soil and climate conditions, *Deschampsia antarctica* communities emit similar amounts of CO_2 when compared to *Sanionia uncinata* carpets. Further studies are necessary to validate this on a broader scale.
3. Spatial variability models derived for soil CO_2 emission indicate smaller ranges (1.3 m) for moss carpets. Soil temperature did not appear to be related to the spatial variability of CO_2 emission. On the other hand, the vegetation distribution was clearly associated with this variability.

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