



CO₂ and N₂O emissions in a soil chronosequence at a glacier retreat zone in Maritime Antarctica



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HIGHLIGHTS

- We evaluated soil organic matter and GHG emissions across a glacier retreat chronosequence.
- Soils exposed for a longer time increased soil organic matter and GHG emissions.
- Degree of humification in soil organic matter tended to be higher in newly exposed areas.
- The results would provide representative data for global warming effects.

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ABSTRACT

Studies of C cycle alterations are extremely important to identify changes due to climate change, especially in the polar ecosystem. The objectives of this study were to (i) examine patterns of soil CO₂-C and N₂O-N emissions, and (ii) evaluate the quantity and quality of soil organic matter across a glacier retreat chronosequence in the Maritime Antarctica. Field measurements were carried out during January and February 2010 (summer season) along a retreating zone of the White Eagle Glacier, at King George Island, Maritime Antarctica. Soil samples (0–10 cm) were collected along a 500-m transect at regular intervals to determine changes in soil organic matter. Field CO₂-C emission measurements and soil temperature were carried out at regular intervals. In addition, greenhouse gas production potentials were assessed through 100 days laboratory incubations. Soils exposed for a longer time tended to have greater concentrations of soluble salts and possess sandier textures. Total organic C (3.59 g kg⁻¹), total N (2.31 g kg⁻¹) and labile C (1.83 g kg⁻¹) tended to be lower near the glacier front compared with sites away from it, which is correlated with decreasing degree of humification of the soil organic matter with exposure time. Soil CO₂-C emissions tended to increase with distance from the glacier front. On average, the presence of vegetation increased CO₂-C emissions by 440%, or the equivalent of 0.633 g of CO₂-C m⁻² h⁻¹. Results suggest that newly exposed landsurfaces undergo soil formation with increasing labile C input from vegetation, accompanied by increasing soil CO₂-C emissions. Despite the importance of exposure time on CO₂-C production and emissions, there was no similar trend in soil N₂O-N production potentials as a function of glacial retreat. For N₂O, instead, the maximum production occurred in sites with the first stages of vegetation growth.

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1. Introduction

The ecosystems of the Maritime Antarctica (between 61°00'–63°37' south, and 53°83'–62°83' west – The South Shetland Islands) are experiencing one of the most rapid localized trends of climate warming worldwide (Convey et al., 2011). Hence, it represents an important

climate sensitive proxy for responses expected in other more complex systems (Convey et al., 2011). Over the past 50 years the Antarctic Peninsula region has warmed by up to 3 °C, more than three times the global mean (Turner et al., 2009; Convey et al., 2011). Despite the extremely low temperatures and dry conditions, the soil environment holds a significant component of the seasonally unfrozen organic carbon reservoir (Burkins et al., 2001). Permafrost-affected soils (Gelisol) contain an estimated 393 Pg of C in the upper 100 cm (Bockheim and Hinkel, 2007), constituting nearly 25% of the global soil organic carbon pool (Lal and Kimble, 2000). Antarctic soils account for as much of 72% of the seasonally unfrozen and biologically available organic carbon, while lakes and streams account for 27 and 0.5%, respectively (Burkins et al., 2001). Soil organic carbon release can be an indicator of regional warming, since this carbon reservoir can be mineralized within relatively short periods (e.g., years versus centuries).

In recent decades, ice recession in the Antarctic Peninsula region has accelerated with global warming to rates that are unprecedented on a global scale (Kozieretska et al., 2010). A consequence of glacier recession is the exposure of formerly ice-covered landscapes to multiple new influences. These include environmental and biological factors, such as exposure to air, occupation by animals (primarily penguins), vegetation establishment, direct rainfall and more profound temperature changes (Simas et al., 2007; Schaefer et al., 2008; Mendonça et al., 2010; La Scala et al., 2010; Strauss et al., 2009; Convey et al., 2011). All these factors control soil formation (Jenny, 1946). One of the most significant soil influences is the penguin excreta accumulation and transformation in breeding places, which reacts with the underlying bedrock forming a layer of phosphorus-rich material, enhancing soil acidification, and plant development (Michel et al., 2006). Glacier recession may also affect surface albedo, biogeochemical weathering reactions, deposition of detritus, soil moisture and temperature fluctuations, and changes in microbial community compositions and activity (Gregorich et al., 2006; Hopkins et al., 2006; Schaefer et al., 2008; Strauss et al., 2009; Mendonça et al., 2010; Convey et al., 2011; Carvalho et al., 2012; Michel et al., 2012). It may result in changing soil respiration rates, affecting the production or consumption of greenhouse gases (GHG) at the glacier retreat zone, especially CO₂ and N₂O.

Along the Antarctica Peninsula, vegetation communities of native flowering plants found on the Antarctic continent (*Deschampsia antarctica* and *Colobanthus quitensis*) and cryptogams (bryophytes and lichens), have increased in size and number over the past 40 years (Smith, 2003; Kozieretska et al., 2010; Convey et al., 2011), partially as a response to glacial retreat (Strauss et al., 2009). These communities have received considerable research attention in recent years in the context of being indicators of biological responses to rapid environmental change (Parnikoza et al., 2009; Kozieretska et al., 2010) and the advanced pedogenetic processes (Simas et al., 2007; Schaefer et al., 2008; Almeida et al., 2014; Michel et al., 2014; Souza et al., 2014). However, vegetation development is highly variable at a glacier retreat zone and influenced by several soil physical (e.g., soil temperature, moisture, permafrost thawing) and biological factors (e.g., microbial community) (Mendonça et al., 2010; Almeida et al., 2014). Thus, alterations on permafrost and microbial communities may drive GHG emission to the atmosphere.

Antarctic soils are key environmental components determining ecosystem C and N cycling processes, such as primary production, decomposition and respiration (Mendonça et al., 2010; Cannone et al., 2012; Carvalho et al., 2012). Soil GHG emissions are influenced by climate changes via increasing temperatures, permafrost thawing, and soil moisture (Cannone et al., 2012; La Scala et al., 2010; Mendonça et al., 2010). The occurrence of vegetation increases the potential of the Antarctic soils to act as sink of atmospheric C, through its retention as organic C in the soil (Park et al., 2007; Cannone et al., 2012). Places with greater vegetation development tend to have greater total soil organic C and N, and GHG emissions (Simas et al., 2007; Carvalho et al., 2012; Vieira et al., 2013; Thomazini et al., 2014), than bare soil sites (La Scala

et al., 2010; Mendonça et al., 2010; Carvalho et al., 2012). Therefore, a large proportion of the C stored in soils is vulnerable for mineralization and subsequent CO₂-C release in the face of current global warming (La Scala et al., 2010). Changes in soil temperature could result in the reduction of the permafrost (Schaefer et al., 2008), increasing losses of C among ice-free soils.

Along a glacier retreat zone, the gradient of soil development, vegetation communities, soil moisture and temperature and soil organic matter may drive GHG and soil organic matter mineralization. Characterization of CO₂-C and N₂O-N emissions in Antarctic soils may help in establishing the relation between soil attributes and climatic changes scenarios along glacier retreat zones (Carvalho et al., 2012). Hence, we aimed to examine (i) patterns of soil CO₂-C and N₂O-N emissions and (ii) evaluate the quantity and quality of soil organic matter across a glacier retreat chronosequence in the Maritime Antarctica.

2. Material and methods

2.1. Site description

The study was carried out at new ice-free areas along the glacier retreat zone of White Eagle Glacier at Admiralty Bay, Low Head Peninsula, King George Island, South Shetland Islands (Fig. 1). There are no local meteorological stations located at Low head. For this reason, climatic data acquired at the Brazilian Commandant Ferraz, the nearest station to Low Head, where mean monthly air temperatures vary from −6.4 °C in July to +2.3 °C in February, and the mean annual precipitation is 400 mm. The mean annual air temperature was −1.1 and −2.6 °C for the years 2010 and 2011, respectively (Almeida et al., 2014). This air temperature and precipitation allows some plant growth, especially mosses, lichens and algae and the two higher plants *D. antarctica* and *C. quitensis* (Convey et al., 2011). Over the past 50 years, several studies have suggested that sea ice in Antarctica is actually decreasing (Gagné et al., 2015). Especially, the White Eagle Glacier front has retreated ~500 m since 1988, exposing soil and forming new ice-free areas (Piotr and Korczak, 2010). The glacier front is at the highest elevation (94 m above sea level) and has no vegetation and low pedogenetic development (Almeida et al., 2014). Permafrost occurs at a depth of 0.96 m (on the average). This zone shows intense frost heaving and cryoturbation during the summer months. The soil is skeletal and classified as a Turbic Haploturbel (Almeida et al., 2014), with a high proportion of coarse grains (>2 mm particles), including rock fragments (>4 mm). The glacial retreat is proceeding along the slope, with an older exposed site at lower elevation locations (29 m above the sea). Here, the parent material is till supplemented by the weathering of local basaltic rocks. When present, the vegetation cover is composed of a mixture of lichens and mosses (*Usnea* sp., *Sanionia uncinata*) and one higher plant (*D. antarctica*). The soil at this retreat zone is a Typic Haplogelepts (Almeida et al., 2014).

2.2. Soil sampling

The soil was sampled in January and February 2010 to determine (i) soil general properties, (ii) total soil organic carbon and total nitrogen, (iii) soil organic matter humification degree, (iv) GC/MS pyrolysis analyses, (v) laboratory GHG production potentials and (vi) microbial biomass carbon. Five soil samples were collected in three locations (hereafter named Sections 1, 2 and 3) at 0–10 and 10–20 cm depth. Section 1 was near the glacier front (from 0 to 150 m), Section 2 was an intermediate location (150 to 300 m from the glacier front) and Section 3 was the farthest point from the glacier front (300 to 500 m) (Fig. 1). The soil samples from the three sections were then thoroughly mixed to form a single homogeneous soil sample for each section and layer, air dried and passed through a 2 mm sieve to determine soil general properties (0–10 cm depth) and the degree of humification in soil organic matter (0–10 and 10–20 cm depth).

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