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Increased CO_2 fluxes under warming tests and soil solution chemistry in Histic and Turbic Cryosols, Salluit, Nunavik, Canada

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ABSTRACT

Cryosols in tundra ecosystems contain large stocks of organic carbon as peat and as organic cryoturbated layers. Increased organic mater decomposition rate in those Arctic soils due to increasing soil temperatures and to permafrost thawing can lead to the release of greenhouse gases, thus potentially creating a positive feedback on global warming. Instrumentation was installed on permafrost terrain in Salluit (Nunavik, Canada; 62°14′N, 75°38′W) to monitor respiration of two Cryosols under both natural and experimental warmed conditions and to simultaneously monitor the soil solution composition in the active layer throughout a thawing season. Two experimental sites under tussock tundra vegetation were set up: one is on a Histic Cryosol (H site) in a polygonal peatland; the other one is on a Turbic Cryosol reductaquic (T site) on post-glacial marine clays. At each site an open top chamber was installed from mid-July to the end of August 2010 to warm the soil surface. Thermistors and soil moisture probes were installed both in natural (N), or non-modified, surface thermal conditions and in warmed (W) stations, i.e. under an open top chamber. At each station, ecosystem respiration (ER) was measured three times per day every second day with an opaque closed chamber linked to a portable IRGA. Soil solutions were also sampled every alternate day at 10, 20 and 30 cm depths and analysed for dissolved organic C (DOC), total dissolved nitrogen (TDN) and major elements. The experimental warming thickened the active layer in the Histic soil while it did not in the Turbic soil. In natural conditions, average ER at the HN station (1.27 ± 0.32 μmol CO_2 m^{-2} s^{-1}) was lower than at the TN station (1.96 ± 0.41 μmol CO_2 m^{-2} s^{-1}). A soil surface warming of 2.4 °C lead to a ~64% increase in ER at the HW station. At the TW station a ~2.1 °C increase induced an average ER increase of ~48%. Temperature sensitivity of ER, expressed by a Q_{10} of 2.7 in the Histic soil and 3.9 in the Turbic Cryosol in natural conditions, decreased with increasing temperatures. There was no difference in soil solution composition between the N and W conditions for a given site. Mean DOC and TDN contents were higher at the H site. The H site soil solutions were more acidic and poorer in major solutes than the T ones, except for NO_3^-. The induced warming increased CO_2 fluxes in both soils; this impact was however more striking in the Histic Cryosol even if ER was lower than in the Turbic Cryosol. In the Histic Cryosol, the thickening of the active layer would made available for decomposition new organic matter that was previously frozen into permafrost; due to acidic conditions, CO_2 would be directly emitted to atmosphere. In contrast, the smaller increase in ER in the Turbic Cryosol may indicate the lack of organic matter input and carbon stabilization because of cold, non-acidic and more concentrated soil solutions; at this site warming mainly stimulates plant-derived respiration without decomposing a newly available carbon pool.

1. Introduction

Permafrost and related Cryosols are considered as the most important terrestrial carbon (C) pool on earth. Therefore permafrost C may have a significant role in the global C dynamics as permafrost thawing under a warming climate could lead to the release of important amounts of greenhouse gases (McGuire et al., 2010; Post et al., 1982; Tarnocai et al., 2009). Although Arctic Cryosols developed in both peat and mineral parent materials (Tarnocai and Bockheim, 2011) represent only 16% of the global soils area, they store 40% of total soil organic C (SOC) within the first metre (Tarnocai et al., 2009). This pool represents more than twice

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the C amount in the atmosphere or in the vegetation (IPCC, 2007; Post et al., 1982). Peatlands in permafrost are the main C pool in northern soils (Tarnocai et al., 2009). Air temperatures within the circumpolar area have been increasing from 1 to 3 °C since the 1960s (ACIA, 2004). Global climate models predict that the mean annual air temperatures would increase from 4 to 7 °C from 1990 to 2090 over the Arctic, including Nunavik, which is twice the global warming rate, with a greater warming in winter than in summer (ACIA, 2004; Allard, 2004). Because of this exacerbated warming in the northern regions, the study of soil organic matter (SOM) dynamics in Cryosols has become essential. Climate change will also dramatically alter precipitation regime and related soil hydrodynamics in still uncertain ways (Schuur et al., 2008).

Warming-induced permafrost degradation might release large amounts of previously frozen organic matter through many processes (Schuur et al., 2008). In addition to accelerated surface soil C decomposition, deep and 'old' C might be increasingly lost to the atmosphere (Dorrepaal et al., 2009; Schuur et al., 2009; Vogel et al., 2009). Particularly, ecosystem respiration (ER) enhancement in Cryosols may contribute to a strong positive climate feedback from terrestrial ecosystems to the atmosphere (Davidson and Janssens, 2006; Schuur et al., 2008; Zimov et al., 2006). Recent coupled climate models of the permafrost-C feedback on global warming pointed to moderate C loss from northern ecosystems (Gao et al., 2013; Koven et al., 2011; Schaefer et al., 2011; Schneider von Deimling et al., 2012). The modelled predictions of C emissions are significantly lower than what could be expected according to the results of field or laboratory experiments (Schuur et al., 2008; Zimov et al., 2006), but modelled results are uncertain due to low-resolution input data and uncertainties in modelling assumptions.

For predicting the magnitude and timing of CO_2 release from Cryosols to the atmosphere, field experiments have to be performed to better understand soil and ecosystem processes: major regulating factors are temperature, soil properties and soil solution chemistry that exert control on ER. A better knowledge and parameterization of processes shall improve calibration and modelling results at the global scale (Dorrepaal et al., 2009; Grogan and Chapin, 2000; van Huissteden and Dolman, 2012).

Laboratory incubations and field experiments at many scales, i.e. from the microbial process scale (Bjork et al., 2007; Deslippe et al., 2012; Elberling et al., 2008; Rinnan et al., 2007; Sistla et al., 2013; Wagner and Liebner, 2009) to the landscape scale (Chapin et al., 2000; Kuhry et al., 2010; Natali et al., 2011; Turetsky et al., 2002), have been used to study the impact of soil warming on C balance in tundra ecosystems. However, field CO_2 flux measurements have been so far mostly performed punctually (Dorrepaal et al., 2009; Grogan and Chapin, 2000; Natali et al., 2011; Pare and Bedard-Haughn, 2012; Schuur et al., 2009; Turetsky et al., 2002; Vogel et al., 2009), which limits extrapolation to the annual timescale.

Indeed, ER depends on various and highly variable factors. ER involves both organic matter decomposition by heterotrophic organisms (microbial activity) and autotrophic respiration (plant-derived respiration) (Kuzyakov, 2006; Turetsky et al., 2002). ER rates depend on physical properties and biogeochemical functioning of Cryosols. At first, soil temperature is likely to be the main control factor of ER (Davidson and Janssens, 2006; Raich and Schlesinger, 1992; von Lutzow and Kogel-Knabner, 2009). The positive effect of raising temperature on organic matter decomposition and primary productivity has been widely demonstrated in northern ecosystems (Dutta et al., 2006; Grogan and Chapin, 2000; Natali et al., 2011). Besides, CO_2 effluxes also depend on soil moisture and water table level (Schuur et al., 2008). Such parameters control soil oxygenation and gas diffusion within the soil profile. Water-logging, which induces anoxic conditions, decreases CO_2 production and emission (Wagner and Liebner, 2009). Finally, the biogeochemical constraints on ER in northern ecosystems were mainly studied through SOM dynamics. Studies based on incubation assays showed great variability in SOM quality among tundra ecosystems, from highly recalcitrant to labile SOM (Hobbie and Gough, 2004; Hobbie et al., 2000) while warming consequences on decomposition differs between these various SOM pools (von Lutzow and Kogel-Knabner, 2009). It has been demonstrated that tundra ecosystems are characterized by low nitrogen (N) contents in soil and vegetation, which limit plant productivity and ER (Hobbie et al., 2002a; Kaiser et al., 2005).

Soil solution is an important control of ER because it provides both nutrients and substrates to plant and microorganisms and integrates products from autotrophic and heterotrophic respiration. Moreover, soil solution acidity, which is dependent on vegetation communities and soil mineral phases, controls both activity and development of plants and microorganisms. Because many feedbacks between vegetation and microorganisms occur in the soil solution, we decided to investigate through field experiments the relationships between biogeochemical composition of soil solution and ER in two contrasted Cryosols. Only a few studies have so far focused on soil solution composition in northern ecosystems (Moore, 2003; Ulanowski and Branfireun, 2013) and its relationship with ER was only investigated in laboratory assays (Hobbie et al., 2002a; Neff and Hooper, 2002).

Closed chambers are the most direct method for measuring ER occurring in soils (Davidson et al., 2002). Associated to soil solution sampling and high frequency ER monitoring, these methods should be suitable to quantify with minimal disturbance CO_2 fluxes and assess related biogeochemical processes that occur in soils.

Our experimental design was set up to answer the following questions: 1) What are the differences and similarities in ER and soil solution composition between a Histic and a Turbic Cryosol differing in parent material and formation history? 2) What is the response of ER to air warming in the two contrasted ecosystems during summer? 3) How are the soil solution composition and the soil properties involved in the response of ER to warming?

We monitored daily variations of ER in the field with a closed chamber as this is the most direct way of measuring ER occurring in soils (Davidson et al., 2002). In combination with the ER measurements, we monitored climate parameters, soil temperature, soil moisture and variations in the composition of soil solution during an entire month of the growth season 2010 in order to get a comprehensive understanding of physical and biochemical controls of ER under both natural (N) and artificially warmed (W) conditions. We instrumented both soils in the surroundings of the Inuit community of Salluit, in Nunavik (Northern Québec, Canada). We installed open-top chambers on each site to mimic a temperature increase of ~2 °C at the soil surface as used in many tundra warming experiments (Dorrepaal et al., 2009; Marion et al., 1997; Natali et al., 2012). To our knowledge, this study is the first *in situ* experiment at the soil profile scale, which simultaneously monitors thermal and hydric regimes, CO_2 fluxes and composition of soil solution at the daily scale over many weeks.

2. Materials and methods

2.1. Study sites

The two study sites and soils are located in the valley of Salluit (62°12′N; 75°38′W), on the south shore of Hudson Strait (Fig. 1). The region has a low arctic climate regime, in the tundra zone. The mean annual precipitation is 310 mm, of which 52% fall as snow (Kasper and Allard, 2001). The mean annual air temperature (1992–2006) is −7.5 °C. However, the mean annual air temperature