Soil Biology & Biochemistry 110 (2017) 34–43

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Regulation of soil organic matter decomposition in permafrost-affected Siberian tundra soils - Impact of oxygen availability, freezing and thawing, temperature, and labile organic matter

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A R T I C L E I N F O

Article history:
Received 22 September 2016
Received in revised form
24 February 2017
Accepted 1 March 2017
Available online 12 March 2017

Keywords:
Permafrost carbon
Incubation
Aerobic
Anaerobic
Priming
Q_{10}
Lena river delta

A B S T R A C T

The large amounts of soil organic matter (SOM) in permafrost-affected soils are prone to increased microbial decomposition in a warming climate. The environmental parameters regulating the production of carbon dioxide (CO_2) and methane (CH_4), however, are insufficiently understood to confidently predict the feedback of thawing permafrost to global warming. Therefore, the effects of oxygen availability, freezing and thawing, temperature, and labile organic matter (OM) additions on greenhouse gas production were studied in northeast Siberian polygonal tundra soils, including the seasonally thawed active layer and upper perennially frozen permafrost. Soils were incubated at constant temperatures of 1 °C, 4 °C, or 8 °C for up to 150 days. CO_2 production in surface layers was three times higher than in the deeper soil. Under anaerobic conditions, SOM decomposition was 2–6 times lower than under aerobic conditions and more CO_2 than CH_4 was produced. CH_4 contributed less than 2% to anaerobic decomposition in thawed permafrost but more than 20% in the active layer. A freeze-thaw cycle caused a short-lived pulse of CO_2 production directly after re-thawing. Q_{10} values, calculated via the equal-carbon method, increased with soil depth from 3.4 ± 1.6 in surface layers to 6.1 ± 2.8 in the permafrost. The addition of plant-derived labile OM (^{13}C-labelled *Carex aquatilis* leaves) resulted in an increase in SOM decomposition only in permafrost (positive priming). The current results indicate that the decomposition of permafrost SOM will be more strongly influenced by rising temperatures and the availability of labile OM than active layer material. The obtained data can be used to inform process-based models to improve simulations of greenhouse gas production potentials from thawing permafrost landscapes.

1. Introduction

Soils and sediments in permafrost regions have accumulated about 1300 Pg of soil organic carbon (SOC), of which about 800 Pg are perennially frozen (Hugelius et al., 2014) and are therefore not part of the active carbon (C) cycle. Hence, permafrost landscapes have been a sink for atmospheric C over thousands of years. Only in the seasonally thawed active layer do soil microorganisms actively decompose soil organic matter (SOM), producing carbon dioxide (CO_2) and methane (CH_4), which may be released back to the atmosphere. In a warmer Arctic, an additional 150–440 Pg of SOC could thaw by 2050 due to permafrost degradation and active layer deepening (Harden et al., 2012). Although it is expected that warming-induced environmental changes will result in higher greenhouse gas fluxes between soils and the atmosphere (Koven et al., 2011; Schneider von Deimling et al., 2012), the factors regulating SOM decomposition in the active layer and thawing permafrost are insufficiently understood.

SOM turnover in permafrost-affected soils is governed by a complex interplay between several environmental parameters such as temperature, moisture, oxygen and nutrient availability, and other soil forming factors, e.g. parent material, SOM quality, and cryoturbation (Hobbie et al., 2000). In addition to low decomposition rates due to low temperatures, impermeable permafrost in the ground impedes water drainage, creating large wetland ecosystems (Lehner and Döll, 2004). In water-logged soils,

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http://dx.doi.org/10.1016/j.soilbio.2017.03.001

anaerobic conditions and the lack of electron acceptors further inhibit anaerobic decomposition processes. Although SOM decomposition is substantially slowed down under anaerobic conditions, the absence of oxygen also favors the production of CH_4, which has a 28–34 times higher warming potential than CO_2 on a century timescale (Myhre et al., 2013). Methanogenesis may principally constitute an important source of greenhouse gases, although the majority of currently available laboratory incubation studies suggest that greenhouse gas production in permafrost-affected soils is dominated by CO_2 (Schädel et al., 2016; Treat et al., 2015).

Temperature is a main driver of microbial processes and higher temperatures increase SOM decomposition rates (Davidson and Janssens, 2006). Old C incorporated in permafrost could be particularly sensitive to temperature changes (Knorr et al., 2005). Temperature may also indirectly influence SOC dynamics. Shifts in plant community structures, higher air temperatures, and rising atmospheric CO_2 concentrations can lead to higher plant net primary production and above-ground uptake of CO_2 (Ainsworth and Long, 2004). Part of this additional C will be transferred into soils, e.g. as plant litter or root exudates (Jastrow et al., 2005). In addition, higher temperatures and associated increases in active layer depths will lead to larger rooting depths and higher C inputs (Jorgenson et al., 2010). This may have contrasting effects on SOC storage. On the one hand, SOM is decomposed more slowly in deeper soil layers and relatively undecomposed material is eventually incorporated into permafrost (Palmtag et al., 2015). On the other hand, the input of fresh and labile OM from the surface may stimulate microbial activity and enhance the decomposition of older SOM through positive priming (Fontaine et al., 2007). Consequently, higher SOM decomposition rates will result in a loss of SOC. Considerable C losses can also be caused by freeze-thaw cycles, which cause short bursts of greenhouse gas production (Matzner and Borken, 2008).

To better understand the effect of different environmental parameters on SOM decomposition in thawing permafrost environments, the current study quantifies the effect of oxygen, freezing and thawing, temperature, as well as the availability of labile OM on CO_2 and CH_4 production in Siberian tundra soils. The multitude of these factors, their interconnections, as well as differences in the response of the active layer and the permafrost to warming-induced environmental changes are still underrepresented in the literature. Therefore, mineral soil samples from the active layer and shallow permafrost were incubated for up to 150 days, which reflects about one thaw period. We hypothesized that (i) SOM in the active layer is decomposed more quickly than in thawed permafrost, (ii) the absence of oxygen reduces the production of greenhouse gases, (iii) freeze-thaw cycles increase the microbial decomposition of SOM, (iv) temperature sensitivity is higher in permafrost than in the active layer, and (v) the addition of labile OM increases the decomposition of autochthonous SOM in the whole soil profile. The obtained data can be used to inform process-based models to improve simulations of greenhouse gas production potentials from thawing permafrost.

2. Material and methods

2.1. Study site

The study site of Samoylov Island (72° 22′ N, 126° 30’ E) is located in the Lena River Delta, northeast Siberia. The Lena River Delta lies within the zone of continuous permafrost and consists of three main geomorphological units (terraces) and the active floodplains (Schwamborn et al., 2002). Samoylov Island is part of the youngest first terrace, which developed during the Holocene. The elevated river terrace is characterized by ice wedge polygons with low-lying polygon centers and elevated polygon rims. The dominating vascular plant species is *Carex aquatilis*, with a total coverage of 25% in polygon centers (Kutzbach et al., 2004). Below ground, *C. aquatilis* forms a dense mat of coarse perennial roots and fine roots can be found down to the permafrost table (Kutzbach et al., 2004). Main soil types (IUSS Working Group WRB, 2014) on the river terrace include Histic Cryosols in polygon centers and Turbic Cryosols in elevated polygon rims (Pfeiffer et al., 2002).

The study site is characterized by an arctic climate with a mean annual (1981–2010) temperature of −12.8 °C and mean annual precipitation of 322 mm (WMO station 218240, Federal Service for Hydrometeorology and Environmental Monitoring of Russia, http://www.meteorf.ru). The ground remains completely frozen from November until June. In the active layer, temperatures above freezing during the summer months enable microbial decomposition of SOM. The mean duration of thaw is 129 ± 10 days and the mean maximum thaw depth of polygon centers is 51 ± 5 cm, with a maximum recorded thaw depth of 61 cm in wet polygons (Boike et al., 2013).

2.2. Soil sampling and analysis

Three different low-centered polygons (Table 1) were sampled on the river terrace. Soil cores were obtained using a portable SIPRE-corer (Jon's Machine Shop, Fairbanks, AK, USA) with a STIHL BT 121 engine (STIHL, Waiblingen, Germany). Coring was conducted in April 2011 (Polygons 1 and 2) and May 2013 (Polygon 3) while the entire soil profile was still frozen. Cores were recovered to depths of 82 cm, 86 cm, and 92 cm.

Frozen soil cores were divided into four soil layers: (i) the surface active layer (0–11 cm) including relatively undecomposed plant material, (ii) the bottom active layer (11–41 cm), both thawing every year, (iii) the transition zone (41–60 cm), which only thaws in some years, and (iv) permafrost (>60 cm), presumably not thawed for several decades to centuries. Cores were further

Table 1
Sample overview, treatments, and soil properties.

Depth (cm)	Layer[a]	Treatment[b]	SOC (mg g^{-1})	C/N	pH	$\delta^{13}C_{SOC}$ (‰ VPDB)
Polygon 1, 72° 22.5 N, 126° 29.3 E						
0–11	sAL	Ae, An, FT	146	27.5	5.63	−28.7
11–22	bAL	Ae, An	100	36.4	5.91	−27.9
22–32	bAL	Ae, An, FT	41	25.0	6.40	−27.5
32–42	bAL	Ae, An	81	29.3	6.66	−26.3
42–51	TZ	Ae, An	59	27.4	6.44	−26.4
51–60	TZ	Ae, An	67	31.9	6.31	−26.3
60–68	Pf	Ae, An	65	30.7	6.13	−26.9
68–77	Pf	Ae, An	73	29.0	6.15	−26.0
77–86	Pf	Ae, An, FT	101	29.0	6.21	−26.5
Polygon 2, 72° 22.3 N, 126° 29.9 E						
0–11	sAL	Ae, An, FT	137	31.5	6.28	−28.1
11–22	bAL	Ae, An	99	29.6	5.36	−27.3
22–32	bAL	Ae, An, FT	87	28.6	5.50	−27.4
32–42	bAL	Ae, An	106	28.2	5.69	−26.4
42–51	TZ	Ae, An	177	32.7	5.64	−25.3
51–60	TZ	Ae, An	107	31.4	5.62	−26.0
60–67	Pf	Ae, An	55	23.4	5.61	−26.6
67–74	Pf	Ae, An	137	31.8	5.41	−26.5
74–82	Pf	Ae, An, FT	84	20.5	5.37	−26.1
Polygon 3, 72° 22.5 N, 126° 29.4 E						
0–10	sAL	Ae, T, P	110	40.3	6.02	−27.4
20–30	bAL	Ae, T, P	52	23.6	6.53	−25.4
70–80	Pf	Ae, T, P	115	21.3	6.45	−26.3

[a] sAL = surface active layer, bAL = bottom active layer, TZ = transition zone, Pf = permafrost.
[b] Ae = aerobic, An = anaerobic, FT = freeze-thaw, T = temperature, P = priming.