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Temperature response of soil organic matter mineralisation in arctic soil profiles

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ABSTRACT

Soil organic matter (SOM) in arctic and boreal soils is the largest terrestrial reservoir of carbon. Increased SOM mineralisation under increased temperature has the potential to induce a massive release of CO_2. Precise parameterisation of the response of arctic soils to increased temperatures is therefore crucial for correctly simulating our future climate. Here, we investigated the temperature response of SOM mineralisation in eight arctic soil profiles of Norway, Svalbard and Russia. Samples were collected at two depths from both mineral and organic soils, which were affected or not by permafrost and were incubated for 91 days at 4, 8, 12, and 16 °C. Temperature response was investigated through two parameters derived from a simple exponential model: the intensity of mineralisation, α, and the temperature sensitivity, Q10. For each sample, SOM quality was investigated by ^{13}C-NMR, whereas bacterial and fungal community structure was characterised by T-RFLP and ARISA fingerprints, respectively. When estimated from the whole incubation period, α proved to be higher in deep permafrost samples than in shallow active layer ones due to the presence transient flushes of mineralisation in deep permafrost affected soils. At the end of the incubation period, after mineralization flushes had passed, neither α nor Q10 (averaging 1.28 ± 0.07) seemed to be affected by soil type (organic vs mineral soil), site, depth or permafrost. SOM composition and microbial community structure on the contrary where affected by site and soil type. Our results suggest that deep samples of permafrost affected soil contain a small pool of fast cycling carbon, which is quickly depleted after thawing. Once the mineralization flush had passed, the temperature response of permafrost affected soil proved to be relatively homogenous among sample types, suggesting that the use of a single temperature sensitivity parameter in land surface models for SOM decomposition in permafrost-affected soils is justified.

1. Introduction

Arctic and boreal soils from the northern circumpolar permafrost region represents more than half of the global soil organic matter (SOM) (Jobbagy and Jackson, 2000; Tarnocai et al., 2009). Most global circulation models tend to predict a 1–3.5 °C increase in mean global surface temperature by the end of the century with a disproportional increase at high latitudes (Houghton, 1996; Räisänen et al., 2004). This increase in temperature may accelerate the decomposition of SOM in high latitude regions, thereby generating large emissions of greenhouse gases (GHG) and a positive feedback on the global temperature (Friedlingstein et al., 2006). Therefore, characterising the intensity of SOM mineralization after thawing and its sensitivity to temperature increase is crucial for predicting the evolution of the Earth's climate. The response of SOM decomposition to increasing temperature, hereafter referred to as SOM temperature sensitivity, appears complex because it results from the interaction of multiple factors and mechanisms (von Lützow and Kögel-Knabner, 2009). Indeed, substrate quality (e.g. Kätterer et al., 1998; Feng and Simpson, 2008;

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Frey et al., 2013), substrate availability (e.g. Gu et al., 2004; Bengtson and Bengtsson, 2007; Gershenson et al., 2009; Fissore et al., 2013), microbial community structure and functioning (Wei et al., 2014), as well as environmental factors (Conant et al., 2011) have been shown to govern temperature sensitivities of both SOM mineralisation rates and C use efficiency. Artic soils have been reported to display contrasting properties as compared to more temperate soils, including SOM and microbial community compositions. In particular, arctic permafrost soils are rich in soluble compounds and cellulose, which could decompose easily under warmer conditions (Michaelson et al., 2004). SOM physically protected in ice clogged aggregates within permafrost layers is in particular expected to become suddenly available after thawing. However, despite the importance of arctic soils, little is known about the dynamic of their organic matter (OM) stocks and their response to global warming (McGuire et al., 2009; Schmidt et al., 2011).

The objectives of the present study are to characterise through laboratory incubations the mineralisation responses of arctic soils to increasing temperature immediately after the thawing, and to further identify potential relationships with SOM composition and microbial community structure. Here, we hypothesise that SOM temperature response in arctic and permafrost affected soils is controlled by environmental factors such as the presence or absence of permafrost, the prevailing organic vs. mineral nature of the soil (hereafter functionally referred to as "soil type") and soil depth.

2. Material and methods

2.1. Soil sampling and physico-chemical characterisation

Eight soil profiles in total were sampled in Adventdalen (A) in Svalbard, Vorkuta (V) in North-Western Russia, and Neiden (N) in Finnmark (Norway). The A1 and A2 profiles are permafrost affected, and according to the last version of the World reference base for soil resources (IUSS Working Group WRB, 2014) are classified as non-cryoturbated Haplic Cryosols. The V1 and V4 profiles are permafrost affected and cryoturbated mineral soils, classified as Turbic Cryosols. The V2 profile is a non-permafrost non-cryoturbated mineral soil, classified as Gelistagnic Cambisol, and V3 is a permafrost affected peat soil belonging to the Cryic Histosol. Palsas are dynamic ice-core peat mounds occurring in polar and subpolar climates, whose genesis and features are well described in Seppälä (1986). The N1 profile is permafrost affected palsa peat classified as Cryic Histosol, and N2 is an adjacent non-permafrost peat soil classified as Hemic Histosol. Soil sampling was conducted between July and September 2008. Profiles were dug in the non-frozen soil and, when applicable, cylindrical cores were drilled or hammered into the permafrost layer. Two large (1–3 kg) bulk samples were taken from each soil profile at two depths, shallow (suffix s) and deep (suffix d), the depths depending on the sampling site (Table 1). In fact, care was taken to avoid the surface soil and the transition zone between active and permafrost layers. For ease of following sample properties, a two-letter descriptor was added to each sample identifier using "A", "P", "O", "M" for "Active layer", "Permafrost layer", "Mineral soil" and "Organic soil". As an example, the following denomination, $V4d_{(PM)}$, designates the sample taken at the bottom of the fourth profile sampled at Vorkuta and indicates that this sample is a permafrost affected mineral soil. All soil samples were kept frozen at −18 °C immediately after sampling until analysis. Aerobic incubations were conducted on field-moist samples, i.e. the soils were never allowed to completely dry out. Frozen soil samples were thawed on filter paper in a 10 °C controlled room and left for 72 h to drain. Aliquots of these samples were taken for soil analyses. Soil pH was measured in deionised water (1:2.5) with a combined Orion pH electrode (SA 720, Allometrics, Inc., Bâton Rouge, LA). Soil gravimetric moisture contents were estimated with oven drying at 105 °C for 48 h. Total C and N were determined by dry combustion using a LECO® CNH1000 analyser. The results were used to recalculate the initial amount of dry soil and total C in the incubated samples (Table 1).

Table 1
Soil sample characteristics.

Sample id#	Coordinates	Depth	Sample type*	$pH_{(H2O)}$	C%	N%	C:N
Svalbard (Norway)							
A1s	N78° 12′05.5″	20–50	S/A/M	4.64	1.39	0.05	29
A1d	E15° 50′03.8″	105–173	D/P/M	4.46	1.76	0.06	30
A2s	N78° 11′09.2″	20–40	S/A/M	5.16	2.47	0.12	21
A2d	E15° 55′29.4″	70–106	D/P/M	4.78	2.14	0.08	28
Finnmark (Norway)							
N1s	N69° 41′05.3″	20–57	S/A/O	3.52	58.85	1.67	35
N1d	E29° 01′57.2″	57–151	D/P/O	4.17	54.37	1.88	29
N2s	N69° 41′06.9″	30–50	S/A/O	4.21	57.46	1.95	29
N2d	E29° 11′46.1″	100–115	D/A/O	4.32	43.90	1.56	28
Vorkuta (Russia)							
V1s	N67°35′23.4″,	20–37	S/A/M	5.81	2.12	0.12	17
V1d	E064°10′00.4″	55–105	D/P/M	6.40	1.36	0.09	16
V2s	N67°35′20.9″,	20–40	S/A/M	4.69	1.85	0.12	16
V2d	E064°09′39.8″	40–80	D/A/M	6.10	0.16	0.01	27
V3s	N67°30′06.4″,	20–50	S/A/O	4.59	53.69	2.85	19
V3d	E064°22′54.3″	60–100	D/P/O	5.51	18.91	1.22	16
V4s	N67°20′35.4″,	20–60	S/A/M	6.43	2.55	0.18	14
V4d	E063°55′46.4″	70–100	D/P/M	7.48	0.36	0.01	26

* Sample types: (S) shallow, (D) deep, (A) active layer, (P) permafrost layer, (M) mineral soil, (O) organic soil.

2.2. Carbon mineralisation measurement

Moist samples at field capacity of mineral and organic soil, 50 and 20 g respectively, were incubated in triplicates in 250-ml serum vials. Prior to capping with CO_2-tight butyl-rubber stoppers, vials were flushed with compressed air. Thorough flushing of the vials containing the soil samples was controlled with an infrared gas analyser (IRGA) (EGM-4 PP System, Amesbury, MA, USA). Flushing time of one minute proved to be sufficient to reach the CO_2 concentration of compressed air, i.e. 147 ± 2 ppm. Butyl-rubber stoppers were partially inserted before removing the flushing tube, so that end of flushing and capping were simultaneous. Serum vials were placed in triplicates in incubators in the dark for 91 days at 4, 8, 12, and 16 °C. Moisture content was kept constant during the course of the entire incubation period by weighing each sample and spraying distilled water to compensate for any water loss. Measurements of soil C mineralisation were performed at approximately two-week intervals over a 91-day period. Carbon mineralisation rates were determined by measuring the accumulated CO_2 concentration in the vial headspace. Measurements were performed with a micro gas chromatograph (Agilent 3000 Micro-GC, France). Samples were flushed and recapped at intervals that prevented the headspace CO_2 concentration to ever exceed 35,000 ppm, the value at which anaerobic thresholds have been reported (MacFadye, 1973). Samples were capped between 4 and 14 days before measurements.

2.3. Analysis of soil organic matter by ^{13}C-CPMAS NMR

Solid-state ^{13}C-CPMAS NMR spectra were recorded on a Bruker AMX 300-WB spectrometer equipped with a 4 mm CPMAS probe. Experimental conditions were: 90° pulse = 3.1 μs, contact time = 3 ms, relaxation delay = 3s, spinning rate = 8 kHz, and number of scans between 8000 and 32,000 depending on the SOM