DIPLOMARBEIT

Titel der Diplomarbeit

The impact of temperature on DOC production and quality in tundra soils

angestrebter akademischer Grad

Magistra der Naturwissenschaften (Mag. rer. nat.)

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Wien, am 30.12.2010

Acknowledgements

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General Introduction

Global Warming

The IPCC defines climate change as a process that continues over a prolonged time period, during which changes in the mean and/or the variability of climate's properties can be identified (IPCC 2007). Over the last decades a warming of the earth's climate could clearly be observed through rising global air and ocean temperatures, increased snow and ice melt and rising sea levels. Although the IPCC's definition of climate change does not address the cause of the climatic changes, current global warming can most likely be linked to increasing greenhouse gas concentrations in the atmosphere, such as carbon dioxide (CO_2) and methane (CH_4) (Dutta, Schuur et al. 2006) that alter the earth's radiation balance, as well as the global carbon (C) Cycle (Forster and G. Raga 2007). At the same time, the $\delta^{13}C$ value of the atmosphere is becoming more depleted. This suggests that the CO_2-C entering the atmosphere derives from plant sources with a C_3 photosynthetic pathway, which are very depleted in $\delta^{13}C$. This depletion of the atmosphere is also more pronounced over the northern hemisphere, which contains larger landmasses. Therefore, the increase of CO_2-C in the atmosphere is probably a result of the anthropogenic burning of fossil fuels that have been derive from C_3 plants (Keeling, Piper et al. 2005). Land use changes, like deforestation and reallocation to agriculture as well as excessive use of fertilizer, also contribute to rising greenhouse gas concentrations in the atmosphere (IPCC 2007). Thus, the alteration of the C cycle and its consequences for global climate can be considered as an anthropogenic process. However, gross natural fluxes of C in and out of terrestrial and ocean reservoirs are an order of a magnitude larger than human-induced changes (Schuur, Bockheim et al. 2008). Therefore it is important to investigate how the natural C pools will react to climatic changes, as only small alterations in natural C cycling processes might have large impacts on the atmospheric C pool (Forster and G. Raga 2007), leading to positive feedbacks on global warming (Cox, Betts et al. 2000).

Among a number of so-called "vulnerable C pools", which might contribute to the increase of C in the atmosphere, the C stored in permafrost soil is of particular importance (Gruber, Friedlingstein et al. 2004) because of the high C content stored in these soils and the greater vulnerability of Arctic and boreal ecosystems to global warming (Hobbie, Schimel et al. 2000; Ford and Furgal 2009).

Arctic ecosystems and Global Warming

Arctic ecosystems are characterized by extreme conditions, such as a short vegetation period, great differences in the photoperiod between summer and winter, low precipitations and extremely cold temperatures during the long Arctic winter. Additionally, frequent mechanical as well as biological disturbances often occur in these ecosystems. Biodiversity is generally low and species are highly adapted to the extreme conditions. These characteristics make the Arctic more vulnerable to disturbances, such as climate warming and associated consequences (ACIA 2005).

Reports such as the Arctic Climate Impact Assessment (ACIA) additionally showed that the Arctic will be more affected by Climate Warming than other ecosystems, with temperatures rising more rapidly and to a greater extend than globally (ACIA 2005). These changes might affect the physical and ecological system of the Arctic as well as the various peoples living in these regions (Hinzman, Bettez et al. 2005). Although the Arctic makes up less than five percent of the earth's surface, it holds high potentials for climate feedbacks and thus Arctic climate change is likely to also influence other regions of the world (Miller, Brigham-Grette et al. 2010). Since the early 1990s annual surface temperatures in the Arctic were above the mean of the 20th century (Richter-Menge 2006). Over the past years, a reduction of the maximum sea ice extent as well as extreme ice extent minima during the summer months could be observed (Perovich and Richter-Menge 2009), while sea levels have risen. Changes in sea-ice cover may also have an impact on the heat flux from land to water and thus influence Arctic vegetation (State of the Arctic 2006). Data from satellite observations indicate increased photosynthetic activity of tundra ecosystems but decreasing activity in boreal regions (Bunn and Goetz 2006). Changes in precipitations may influence hydrological conditions as well as winter snow cover

that may impact plant growth, soil insulation and decomposition processes (Miller, Brigham-Grette et al. 2010). And all these changes will affect the Arctic C cycle.

Arctic Carbon Cycling

Northern latitude ecosystems have served as C sinks for thousands of years (Waldrop, Wickland et al. 2010). This means that more C is fixed in plant biomass by photosynthesis than is respired to the atmosphere (Kling, Kipphut et al. 1991). However, these ecosystems have the potential to be turned into a C source at warmer temperatures. C is predominantly stored in terrestrial Arctic systems as soil organic C (SOC) and in living biomass, with the amount of C stored in soils being two magnitudes larger than the biomass C stock (McGuire, Anderson et al. 2009).

The C dynamics of the Arctic Ocean are influenced by inputs from the Atlantic and Pacific Ocean as well as terrestrial river runoff and therefore show a high seasonal variability (Holmes, Peterson et al. 2000). Arctic Ocean sediments store high amounts of particulate C. Transfer of C from terrestrial and aquatic stocks to the atmosphere can occur through CO_2 and CH_4 emissions. Lateral transport of C from Arctic soils via Arctic rivers to the Arctic ocean occurs as dissolved or particulate organic or inorganic C (DOC, POC, DIC, PIC) (McGuire, Anderson et al. 2009). Climate warming may influence these stocks and transport pathways directly as well as indirectly and holds the possibility of positive as well as negative feedback on the C cycle. Higher temperatures, longer vegetation periods and higher atmospheric CO_2 concentrations are likely to increase Net Primary Production (NPP), thus more C could be stored in living biomass (Cox, Betts et al. 2000; Luo 2007). On the other hand, drought stress, forest degradation and increased fire frequency (Kasischke and Turetsky 2006) will release more CO_2 to the atmosphere. Also, higher temperatures will enhance microbial activity and thus increase CO_2 and CH_4 emissions to the atmosphere, both from terrestrial as well as aquatic systems (Wickland, Neff et al. 2007). The decrease in sea-ice cover of the Arctic Ocean that could be observed over the last decade (Perovich and Richter-Menge 2009) will increase the efflux of CO_2 to the atmosphere and enhance biological activity through higher light input into the

surface layers of the Arctic Ocean. The thawing of sea bed permafrost might also increase CO_2 and CH_4 emissions (McGuire, Anderson et al. 2009). Additionally, climate warming will lead to permafrost degradation (Lawrence and Slater 2005), which will have important consequences for the Arctic C cycle and represents one of the major potential feedbacks from Arctic terrestrial ecosystems (Schuur, Bockheim et al. 2008).

Permafrost, Carbon Storage and Climate Feedbacks

Permafrost soils are defined as soils exhibiting temperatures lower than 0°C for a period longer than two consecutive years (Schuur, Bockheim et al. 2008). This type of soil is widespread in Arctic and boreal regions and covers up to 25% of the northern hemisphere. During the summer months a surface layer unfreezes, forming the so-called "active layer". The active layer can vary in thickness from centimetres to metres, depending largely on local climate (Schuur, Bockheim et al. 2008) and is of importance as most chemical processes take place in this layer (Frey and McClelland 2009).

The C content in permafrost soils is high due to various reasons: Conditions such as low temperatures and high soil moisture are unfavourable for rapid soil organic matter decomposition leading to accumulation of organic matter (McGuire, Anderson et al. 2009). Low temperatures and water saturation in poorly drained areas promote vertical peat formation, resulting in an accumulation of organic C due to reduced decomposition of organic matter (Gorham 1991; Clark, Ashley et al. 2009). During the Pleistocene deposition of C rich aeolian or alluvial sediments, such as Yedoma, took place over the mammoth steppe tundra ecosystem. These sediments, which exhibit an especially high content of labile C, were incorporated into the permafrost (Zimov, Davydov et al. 2006; Zimov, Schuur et al. 2006). Cryoturbation, soil movements due to freeze-thaw cycles, can redistribute soil organic C (SOC) from surface layers into deeper soil layers, where microbial activity and therefore microbial decomposition of SOC is slower (Bockheim 2007).

The large C stocks in permafrost soils have been the focus of various studies over the past years to ascertain their response to climate warming and the

resulting implications for the global C cycle (Dutta, Schuur et al. 2006; Zimov, Schuur et al. 2006; McGuire, Anderson et al. 2009; Schuur, Vogel et al. 2009; Tarnocai, Canadell et al. 2009). Increasing summer temperatures will lead to permafrost thaw, which may occur gradually through active layer thickening or through thermokarst development. This process happens through thawing of soil ice that leads to the collapse of soil, forming depressions in the landscape, and can have important consequences for the C cycling as it alters hydrological conditions (Schuur, Bockheim et al. 2008). Increasing winter precipitations and snow cover have an insulating effect on permafrost temperatures and lead to deeper thawing of the active layer during summer (Zhang 2005). Models predict substantial loss of near surface permafrost throughout the 21st century, a reduction of permafrost extent and a deepening of the active layer depth (Lawrence and Slater 2005).

Permafrost degradation may alter drainage conditions of the soil and lead to an increase in river discharge, which will have an impact on Arctic river biogeochemistry (Frey and McClelland 2009). Increasing discharge to the Arctic Ocean will increase the nutrient availability in the surface layer of the ocean and thus may increase biological activity and CO_2 emissions (McGuire, Anderson et al. 2009). Active layer thickening may render formerly frozen SOC available for microbial decomposition. Because decomposition rates are slow in Arctic soils, the stored organic C is labile (Waldrop, Wickland et al. 2010) and thus might be easily decomposed by soil microbes once soil temperatures exceed 0°C, leading to increased CO_2 emissions to the atmosphere (Davidson and Janssens 2006). Estimations concerning the total amount of C stored in permafrost soils vary widely as a result of different depth ranges in soil horizons when assessing C stocks and the unknown depth of peat in peat lands (McGuire, Anderson et al. 2009). Schuur, Bockheim et al. (2008) estimate the total soil C to be 1672 Pg, admitting that this could be an underestimation. McGuire, Anderson et al. (2009) estimate total soil C storage to be between 1400 and 1850 Pg. Xu, Guo et al. (2009) deem Arctic tundra ecosystems to contain up to 30% of the global soil organic carbon pool, which would be much less than the above estimates. Tarnocai, Canadell et al. (2009), including new data from deep soil layers, agree with Schuur's lower estimate. This implies that C stored in northern circumpolar

permafrost soils makes up 50% of the global soil organic C pool. In general, the northern circumpolar soil C pool has been underestimated in the past and estimations have risen over the last years, to more than double of previous estimates (Jobbagy and Jackson 2000).

C in northern permafrost soils is stored and released in different pools and fractions that will respond differently to climate warming. CH_4 is emitted to the atmosphere by anaerobic decomposition of SOC in peat lands and wetlands. It is also stored in the form of methane hydrates, which are solid, ice-like substances enclosing CH_4 in a cage structure of water molecules. Methane hydrates are only stable under high pressure and/or low temperatures, but may dissociate under changing environmental conditions, releasing high amounts of CH_4 to the atmosphere (Kvenvolden 1994). Aerobic decomposition of SOC releases CO_2 to the atmosphere through soil respiration. SOC can also be removed from the soil through leaching as dissolved organic carbon (DOC) or particulate organic carbon (POC). Carbon stored in calcareous rocks might be removed as dissolved inorganic carbon (DIC) or particulate inorganic carbon (PIC) (McGuire, Anderson et al. 2009).

DOC and Carbon Cycling

In the past years, many studies focused on increasing CH_4 and CO_2 emissions (Kvenvolden 1994; Kvenvolden 2002; Davidson and Janssens 2006; Walter, Zimov et al. 2006; Schuur, Vogel et al. 2009). However, little is known about what changes climate warming may trigger in DOC production and their consequences for C cycling in the Arctic, although due to the large stocks of organic C as well as the slow decomposition rates, Arctic soils display a potentially large DOC source (Wickland, Neff et al. 2007).

DOC is an operational classification, defining matter passing through a 0.2 μm filter (Belzile, Roesler et al. 2006) and referring to the soluble fraction of the carbon stock of ecosystems. It consists of a complex mixture of different organic substances, which exhibit different molecular weights, such as amino acids, sugars, humic acids and fulvic acids (Wickland, Neff et al. 2007; Moore, Pare et al. 2008). DOC originates from different sources, such as vegetation, litter or

microbial biomass and is produced through abiotic as well as biotic processes mainly from the SOC pool (Wickland, Neff et al. 2007). It serves as the primary C source for terrestrial as well as aquatic microorganisms and is thus a substrate for microbial activity (Bengtson and Bengtsson 2007).

The hydrologic cycle in the Arctic is characterized by the particular conditions generated by permafrost (Kling 1995). The frozen layer of permafrost serves as a physical barrier and prevents percolation of water into deep soil, limiting ground water formation and movement to the upper layers (Wickland, Neff et al. 2007). Thus, the potential for transport from land to water is higher in regions underlain with permafrost (Judd and Kling 2002) and the hydrologic cycle shows a strong seasonal aspect as it is controlled by freezing and thawing of the soil (Lobbes, Fitznar et al. 2000). Terrestrial inputs into the aquatic system encompass water, inorganic nutrients and organic matter. These inputs have a strong regulatory function on aquatic ecosystems (Kling 1995). DOC inputs provide an important source of C for aquatic microorganisms (Judd and Kling 2002), which take up labile components of DOC, thus incorporating DOC into the aquatic food web, making it available to higher trophic levels (Rublee 1992). DOC composition is further altered during its transport towards the Arctic Ocean. Chemical transformation of organic matter in terrestrial ecosystems will have an impact on its decomposition in aquatic systems (Kling 1995). Therefore the quality of DOC, its chemical composition as well as its potential biodegradability, is crucial for aquatic microbial activity (Judd and Kling 2002) and DOC transformation (Marschner and Kalbitz 2003).

Arctic river discharge is highly seasonal, with more than 90 percent of annual discharge occurring from May to July (Dittmar and Kattner 2003). Riverine flux of C from soils towards the Arctic Ocean constitutes a key connection between terrestrial and marine components of the Arctic C cycle (McGuire, Anderson et al. 2009). The Arctic Ocean is the ocean that receives the highest terrestrial freshwater and organic matter inputs, as it receives ten percent of global river discharge although it presents only one percent of the global ocean volume (Dittmar and Kattner 2003; Hansell, Kadko et al. 2004).

Higher soil temperatures will affect microbial activity (Christ and David 1996) and thus are likely to increase potential production of DOC in Arctic soils (Neff and Hooper 2002) and change the chemical characteristics of DOC (Xu, Guo et al. 2009). Changes in hydrologic conditions of soils due to active layer thickening may increase the residence time of DOC in the soil as well as river discharge (Wickland, Neff et al. 2007; Frey and McClelland 2009). Elevated river discharge of nutrients and organic matter into the Arctic Ocean was observed during the last decade (Dittmar and Kattner 2003). Although the fate of Arctic river DOC in the Arctic Ocean is not entirely clear (Raymond, McClelland et al. 2007), changes in river discharge and the chemical composition of DOC will clearly affect the Arctic Ocean's ecosystem and thus Arctic C cycling as a whole (Holmes, Peterson et al. 2000).

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Manuscript:

"The impact of temperature on DOC production and quality in tundra soils"

Abstract

The large carbon (C) stocks in Arctic permafrost soils are likely to be affected by climate warming. Warmer temperature might lead to increased decomposition and CO_2 and CH_4 release to the atmosphere, which in turn could lead to a positive feedback on climate warming. Little is known about the potential production and the chemical composition of dissolved organic carbon (DOC) in tundra soils and the response of aquatic systems to potential changes in DOC quality. This study aimed at testing the hypothesis that higher temperatures will lead to an increase in DOC production, but to a decrease in the decomposability of DOC (DOC quality). Towards this end, we conducted an incubation experiment with tundra soils from Greenland and Siberia at three different temperatures (4°C, 10°C, 15°C) and monitored DOC production and quality over eight weeks. The bioavailability of the produced DOC was tested in a second experiment, where microorganisms from Greenlandic and Siberian rivers received DOC from the first experiment (i.e., produced at the different temperature) as substrates. Temperature was found to be a significant factor for microbial activity and DOC production, with higher production rates found at higher incubation temperatures. A constant proportion of total soil organic carbon (SOC) was leached as DOC in the two soil types tested. DOC quality was assessed using spectrophotometric and fluorometeric methods. Over the incubation time, DOC got depleted in labile substances, and this depletion was more pronounced and faster for higher incubation temperatures. The bioavailability experiment showed a weak trend that samples incubated with DOC derived at 15°C exhibited a lower CO_2 production rate. Overall, however, the DOC produced at the different temperatures did not exhibit significantly different microbial decomposition. Our results suggest that rising temperatures in the Arctic may lead to an increase in the amount of DOC leached from permafrost soils that will be more depleted in

labile substances. DOC produced at higher temperatures, may thus be decomposed at rates similar to those produced at cooler temperatures.

Introduction

Northern latitude soils are known to store large amounts of C (Hobbie, Schimel et al. 2000; McGuire, Anderson et al. 2009; Xu, Guo et al. 2009). As the Arctic will be more affected by climate change than any other parts of the earth (ACIA 2005), the decomposition of these large C stocks have been the focus of various studies over the past years to establish their response to global warming (Dutta, Schuur et al. 2006; Zimov, Schuur et al. 2006; McGuire, Anderson et al. 2009; Schuur, Vogel et al. 2009; Tarnocai, Canadell et al. 2009).

Current estimates of the total amount of C stored in permafrost soils vary widely but generally these C stocks were underestimated in the past. Estimates have increased over the last years, being now more than double that of previous estimates (Jobbagy and Jackson 2000; Schuur, Bockheim et al. 2008; McGuire, Anderson et al. 2009). Recent total soil C stocks were estimated to be about 1672 Pg in the northern circumpolar permafrost region (Tarnocai, Canadell et al. 2009), which implies that C stored in soils of these regions makes up more than 50% of the global soil organic C pool. An increase in contribution of these C pools to the global C cycle could significantly alter C distribution and lead to positive feedbacks on Climate Warming (Cox, Betts et al. 2000).

C stored as soil organic C (SOC) might be released as CO_2 through soil respiration or removed through leaching as dissolved organic carbon (DOC) or particulate organic carbon (POC). In addition, carbon from peat lands and wetlands is often emitted as CH_4 to the atmosphere and methane hydrates, stored in permafrost soils and sediments (e.g. in the East Siberian shelf region), might become unstable under a warming climate, releasing high amounts of CH_4 to the atmosphere (Kvenvolden 1994). C stored in calcareous rocks might be additionally removed as dissolved inorganic carbon (DIC) or particulate inorganic carbon (PIC) (McGuire, Anderson et al. 2009).

Whereas much focus has been laid on increasing CH_4 and CO_2 emissions (Kvenvolden 1994; Kvenvolden 2002; Davidson and Janssens 2006; Walter,

Zimov et al. 2006; Schuur, Vogel et al. 2009), less is known about the chemical composition and the potential production of DOC under climate warming (Neff and Hooper 2002; Xu, Guo et al. 2009). DOC is an operational classification, defining particles smaller than 0.2 µm (Belzile, Roesler et al. 2006) and is the soluble fraction of the carbon stock. Being produced by abiotic as well as biotic processes mainly from the SOC pool, it consists of a complex mixture of organic substances (Moore, Pare et al. 2008) and serves as the primary C source for terrestrial as well as aquatic microorganisms (Bengtson and Bengtsson 2007). Permafrost prevents percolation of water into deep soil layers, reducing vertical drainage (Wickland, Neff et al. 2007). Thus there is a high potential of lateral DOC transport from land to water (Judd and Kling 2002) so that DOC serves as a link between terrestrial and aquatic ecosystems (Wickland, Neff et al. 2007). As net primary production (NPP) is low in Arctic streams, terrestrial DOC inputs provide an important source of C for aquatic microorganisms (Judd and Kling 2002). Microorganisms take up labile components of DOC, incorporating DOC into the food web, and altering DOC composition during its transport towards the Arctic Ocean (Cole, Prairie et al. 2007). Therefore the "quality" of DOC – i.e., its potential for uptake by microorganisms (bioavailability) as well as its actual utilization (biodegradability) (Marschner and Kalbitz 2003) – is crucial for aquatic microbial activity (Judd and Kling 2002) and DOC transformation. Arctic streams and rivers transport high amounts of dissolved organic matter (DOM) towards the Arctic Ocean, (Hansell, Kadko et al. 2004) and riverine flux of C from soils towards the Arctic Ocean constitutes a key connection between terrestrial and marine components of the Arctic C cycle (McGuire, Anderson et al. 2009). Permafrost degradation is thought to lead to higher river discharge (Frey and McClelland 2009), and the consequences of such an increased discharge on DOC dynamics remains to be elucidated. Although the fate of the terrestrial DOC in the Arctic Ocean remains poorly understood, it is clear that a change in the quantity and quality of DOC leached from Arctic soils will have impacts on the Arctic Ocean (Hansell, Kadko et al. 2004).

The aim of this study therefore was to analyse changes in quantity and quality of DOC produced in permafrost soil under global warming and to analyse the impact of such changes for Arctic aquatic microbial communities. The main research

questions were (a) how the quantity and the quality of DOC produced in Arctic soils under rising temperatures will change and (b) what effect these changes might have on the biodegradability of this DOC for aquatic microorganisms. As DOC production is usually strongly correlated with microbial activity (Christ and David 1996), we hypothesized that a rise in temperature will lead to an increase in DOC production, and thus to an increase in the quantity of leached DOC. On the other hand, higher microbial activity may lead to a more rapid consumption of labile DOC components. Thus, we further hypothesized that an increase in temperature might result in a decrease of the quality of DOC.

To address these questions we conducted two experiments. First, we incubated permafrost soils from Greenland and Siberia at three different temperatures (4°C, 10°C, 15°C) and monitored DOC production and quality. In a second experiment we incubated aquatic microorganisms from Siberian and Greenlandic rivers with DOC of different qualities obtained from the first experiment to test its biodegradability.

Methods

Soil sampling

Soil and microbial samples from Greenland were taken in August 2008 near the Arctic station, situated on the south coast of Disco Island (69° 15' 06'' N, 53° 29' 21'' W). The soil (A-horizon of a gleyic cryosol) was sieved on spot, transported to Austria and stored frozen. Two weeks prior to starting the experiment the soil was thawed at 4°C to gently unfreeze it. Samples from Siberia were taken in August 2009 from an A-horizon (turbic, histic cryosol) located near Tazovsky (67°27'15'' N, 78°83'12'' E). After the transport to Austria, the soil was frozen. Prior to the experiment the soil was unfrozen as described above, sieved and stored at 4°C.

Incubation experiment

Permafrost soils from Greenland and Siberia were incubated over eight weeks at three different temperatures and leached every two weeks. Six replicates were set up for each temperature and each soil type, respectively.
For this experiment, 20 g of soil were weighed into 60 mL syringes that were cut at the top. To prevent soil from trickling out of the syringes, a two cm thick layer of glass wool was fitted at the bottom of each syringe. To support it, a metal grid was put at the bottom and two plastic mesh discs were put at the top and bottom of the glass wool. All tools were pre-washed with 0.1 M HCl.

After establishing the experimental setup, the syringes were stored at 4°C for two days. Before the incubation at different temperatures, all replicates were leached once and their microbial respiration was measured.

Microbial respiration measurements were conducted every two weeks prior to leaching with the "head-space method": a flexible vacuum tube and a long Plexiglas tube were plugged into each other and put on top of the syringes. They were closed with Suba Seals at the top. 15 mL air samples were taken immediately after closing as well as 3, 8, 14, 24 hours later, to measure CO_2 evolution inside the headspace. The air samples were taken with a syringe and a needle and stored in pre-evacuated exetainer flasks. The sample volume was

replaced with synthetic, CO_2-free air. To provide air-tightness the seals were covered with silicone gel during measurements. The gas samples were analysed with a Finnigan GasBench joined with a Finnigan Delta V Advantage Mass Spectrometer (Thermo Fisher Scientific, Whaltham, MA, USA). Respiration rate was determined by using a linear regression model: CO_2 (ppm) = a t + b, a being the respiration rate, t the incubation time in hours and b the intercept. Respiration data was normalized to the dry weight of the replicates.

Leaching was conducted by placing the syringes on a vacuum manifold, supplied by a stop-cock (one-way Luer-lock) and an online filter station (Whatman GF/C filters, 25 mm). The samples were leached with 100 mL of 0.005 M K_2SO_4 (Moore, Pare et al. 2008). After all the liquid was sucked through, the soil samples were exposed to the vacuum for another hour to obtain primary moisture. Leachate was collected in pre-combusted 100 mL Schott-bottles, then filtered again through 0.22 µm polysulfone filters into 40 mL pre-combusted glass vials and stored at 4°C.

Samples were incubated for a period of eight weeks and leached every two weeks. Respiration was always measured before leaching. After the experiment, the samples were deep-frozen. DOC and TN quantity of the leachate were determined with a Total Organic Carbon/Total Nitrogen analyzer (Shimadzu, TOC-V$_{CPH/CPN}$) and the content was normalized to the dry weight of the soils. DOC quality was determined optically with a fluorometer and a spectrophotometer.

Inoculation experiment

Microbial communities from Greenlandic as well as Siberian rivers were stored on filters and frozen and/or stored at 4°C in 15 mL Greiner vials. 10 mL of GF/F and polysulfone filtered nutrient-rich stream water from the Sulzbach near Spannberg (lower Austria) were added and then the vials were shaken on a vortex for about one minute. After the particulate material had sedimented, 5 mL of the supernatant were merged with 25 mL polysulfone filtered stream water in 100 mL pre-combusted Erlenmayer flasks. The flasks were stored in the dark at 10°C. After two weeks, samples to determine bacterial density were taken (5 mL + 2 mL

37% Formol), stained with DAPI and bacterial cells counted with a fluorescence microscope. The bacterial densities on the cooled filters were in the same range:

Siberia: 284×10^5 cells mL^{-1}, Greenland: 251×10^5 cells mL^{-1}.

The cultures were filtered again through GF/C filters to exclude seeders. 20 mL of the inoculum of each region were filtered onto three different polysulfone filters (~6 mL/filter) and the bacteria were dissolved from the filters by adding 10 mL of DOC from the incubation experiment and shaking them on a vortex for about two minutes. The liquid was merged with the remaining DOC. 20 mL of DOC were put into 100 mL Erlenmayerflasks with a ground joint that were sealed with Suba Seals. To provide a growing surface for the bacteria, a quarter of a pre-combusted GF/C-filter was added to each flask. We used five replicates per temperature and soil.

The flasks were sealed and 60 mL of air was removed from each flask and replaced with synthetic air. Then the first gas-samples were taken with a needle into pre-evacuated exetainer flasks and replaced with synthetic air. To provide air-tightness the seals were covered with silicone gel.

The flasks were stored dark on a shaker (10 rpm) at 10°C for 4 weeks. Each week, gas samples were taken as described above. Respiration rates were determined by using a linear regression model: CO_2 (ppm) = a t + b, where a is the respiration rate, t the incubation time in hours and b the intercept.

At the end of the experiment, 10 mL samples for bacterial density were taken from each replicate. The liquid was then filtered through 0.22 polysulfone filters to remove the bacteria and the filtrate was stored in pre-combusted vials for DOC analysis.

DOC quality

DOC quality was analysed optically by using a fluorometer and a spectrophotometer (F-7000 Fluorescence Spectrometer, Hitachi and UV-1700 PharmaSpec, Shimadzu). Samples were prefiltered and warmed to room

temperature before measurements. Milli Q water was run through both instruments to establish a baseline. The following parameters and ratios were measured:

Absorbance spectra

The absorbance spectra were measured between 250 nm and 700 nm, and wavelengths were calculated by converting the absorbance units to absorption coefficients, following the equation $a = 2,303\ A/l$, where a = Naperian Absorption Coefficient (m^{-1}), A = absorbance and l = path length of the cuvette (m). The cuvette used for analysis was chosen according to DOC concentrations in the samples (0.05 m - 0.1 m length). Absorbance spectra can give information about the amount of chromophoric or colored dissolved organic matter (CDOM) (Helms, Stubbins et al. 2008)

Absorbance ratio

The ratio of absorption at 250 nm and 365 nm, also referred to as E2:E3, tracks changes in the relative size of DOM molecules as it decreases with increasing molecular weight (Peuravuori and Pihlaja 1997). It was calculated by taking the corresponding values for these wavelengths from the absorbance spectra.

Specific UV absorbance (SUVA)

The $SUVA_{254}$ was calculated by dividing the UV absorbance at 254 nm to DOC concentration (mg/L). $SUVA_{254}$ correlates strongly with DOM aromaticity (Weishaar, Aiken et al. 2003)

Spectral Slopes (S) and Slope ratio (S_R)

Spectral slopes were calculated by fitting the absorption data to the following equation: $a\ \lambda = a\ \lambda_{ref}\ e^{-S\ (\lambda - \lambda ref)}$, where a = Naperian Absorption Coefficient (m^{-1}), λ = wavelength (nm) and λ_{ref} = reference wavelength (nm). Two spectral slopes S (275-295) and S (350-400) were calculated and their slope ratio (S_R) was calculated to obtain a dimensionless parameter. S_R correlates inversely with the molecular weight (MW) of CDOM (Helms, Stubbins et al. 2008).

Fluorescence Index (FI)

The FI is the ratio of emission intensity at a wavelength of 450 nm to that at 500 nm, obtained with an excitation of 370 nm (McKnight, Boyer et al. 2001). The

index gives information about the source of the fulvic acids. If the index has a value around 1.9, the fulvic acids are of microbial origin, if its value is around 1.4, the source is terrestrial. Intermediate indices indicate the fulvic acids to originate from both microbial and terrestrial sources (ibid.).

Additional Analysis

Dry weight and water content of soil were determined by weighing 5 g of soil into aluminium cups and drying them over night in a drying cabinet at 100°C (five replicates per soil).

Total Organic Carbon and Nitrogen content of the soils was measured with an EA/IRMS (Carlo Erba EA 1110) and C:N ratios were calculated (3 replicates per soil).

Calculations and Statistical Analyses

Calculations of respiration rates were computed with Microsoft Excel (2007). Statistical analyses were conducted with StatGraphics (version 5.0). One-way-ANOVAs were run to analyse differences between the treatments for each time point as well as changes over time for each treatment. The datasets of Siberia and Greenlandic soil were separated for these analyses as they proved to be too different. Tukey was used as a post-hoc test at the 0.95 confidence level (p=0.05).

Results

Incubation experiment

DOC production

When calculated on a soil dry weight (DW) basis, DOC production was four times higher in soils from Siberia than in soils from Greenland. Production rates ranged between 22 and 35 µg C g^{-1} DW and between 5 and 10 µg C g^{-1} DW for Siberian and Greenlandic soils, respectively (Figures 1a, 1b). However, when normalized to the total soil C content, DOC production rates were similar for both soils, with values between 0.086 and 0.18 µg DOC-C mg^{-1} (Figures 1c, 1d).

Temperature significantly influenced DOC production in both soils. Significant differences between the temperature treatments were already visible after two weeks of incubation. After eight weeks, DOC production of both soils was highest for the 15°C treatments, and the 10°C treatments showed higher DOC production than the 4°C treatments. The 15°C treatments were significantly different from the 4°C treatments, whereas the 10°C treatments were not different from either of these treatments (Figures 1a, 1b). While DOC production of Siberian soil remained more or less constant during the course of the experiment, production decreased for the 4°C and 10°C treatments of the Greenlandic soils from week two to week six of incubation (Figure 1a, 1b and Table 1). Accumulated values of DOC production showed two different patterns for each soil: For the Greenlandic soil accumulated DOC values from the 10°C treatment were similar to those from the 15°C treatment after two and four weeks of incubation, and for the rest of incubation time all temperature treatments were different from each other. Accumulated DOC values of the Siberian soil showed a pattern where the 10°C treatment wasn't different from the 4°C or the 15°C treatment during week two to six of incubation and at the end of incubation time was similar to the 4°C treatment (Figure 1e, 1f).

DOC:TDN

Ratios of DOC to Total Dissolved Nitrogen (TDN) varied widely during the incubation experiment. DOC:TDN ratios from both soils showed a pattern: the incubations at 10°C and 15°C were similar throughout the experiment, but were

significantly different from the 4°C incubations. For the Siberian soil the DOC:TDN ratios at 10°C and 15°C already decreased after two weeks of incubation from 4.6 and 4.2 to a range between 2.6 and 3.6 respectively, but increased at 4°C from 3.6 to 6.5 after two weeks and decreased after six weeks to values similar to those of the 10°C and 15°C incubations (Figure 1h). Soils from Greenland showed an inverted pattern with ratios at 10°C and 15°C increasing from values between 2.1 and 1.4 up to 9.2 and 8.1 after two weeks, but dropping to values around 3.7 thereafter. DOC/TDN ratios at 4°C increased more slowly, with a maximum of 8.1 only after six weeks of incubation and dropped afterwards. At the end of the experiment no significant differences between the treatments could be observed (Figure 1g).

Microbial Respiration

Respiration was higher in Siberian soils. It peaked after two weeks with 12.6 and 7.8 µg CO_2 d^{-1} g^{-1} dry soil for the 10°C and 15°C treatments, respectively, followed by a rapid decline of respiration rates. The 4°C treatment showed low respiration rates at the beginning of the incubation experiment but rates increased over time, reaching a maximum of 5.7 µg CO_2 d^{-1} g^{-1} dry soils after six weeks of incubation. At the end of the experiment, respiration rates were in the same range as at the beginning and no significant differences between the three temperature treatments could be observed (Figure 2b). For the Greenlandic soil, a trend similar to the 10°C and 15°C incubations of Siberian soil could only be observed for the 15°C treatment, which exhibited respiration rates with a peak of 2.4 µg CO_2 d^{-1} g^{-1} dry soils after two weeks of incubation, followed by a decrease. The pattern of respiration rates of the 10°C treatment of the Greenlandic soil were similar to those of the 4°C treatment of Siberian soil, with a peak of 1.9 µg CO_2 d^{-1} g^{-1} dry soils after six weeks of incubation, whereas the rates at 4°C of the Greenlandic soil showed little change over the time of the experiment (Figure 2a).

CO_2:(DOC+CO_2) ratios

The ration of CO_2:(DOC+CO_2) describes the respired CO_2 as a fraction of the total C lost from soils through leaching and respiration. In our experiment between 45% and 85% of the losses occurred through DOC leaching for the whole incubation period. After two weeks of incubation, the ratio was generally higher for soils from Siberia but in the end of the incubation it was higher for soils

from Greenland (Figure 3a, 3b). Greenlandic soils showed a decrease of the ratios from the 15°C treatment between week two to six and an increase thereafter. This trend was similar to the 10°C and 15°C treatments of Siberian soils, with ratios of both treatments decreasing from week two to six. For Greenlandic soils, the ratios from the 10°C incubations showed a steady increase, a trend that was also visible for the ratios of the 4°C incubation (Figure 3a). Ratios of the 4°C treatment of Siberian soils did not change significantly over the eight weeks of incubation (Figure 3b).

DOC quality

The ratio of absorbance at 250 nm to 365 nm, also referred to as E2:E4, is known to decrease with increasing molecular weight of the DOC (Peuravuori and Pihlaja 1997). The E2:E4 ratios showed the same pattern for both soils: during the course of the incubation, the ratios dropped from values between 5 and 6 to values between 4 and 4.6. Already two weeks after incubation, the E2:E4 ratios of DOC derived from the different temperature treatments showed significant differences. DOC ratios of Siberian soils showed significantly higher values at 4°C than at 10°C and 15°C, which were not significantly different (Figure 4b). For Greenlandic soils, DOC ratios exhibited a similar trend as the Siberian soils, with values at 4°C being significantly higher than that of the 10°C and 15°C incubations (Figure 4a).

The slope ratio (S_R) of DOC absorbance of 274-295 nm and 350-400 nm correlates negatively with the molecular weight of DOC (Helms, Stubbins et al. 2008). S_R of DOC of Siberian soils showed a similar picture than that of the absorbance ratios (Figure 4d). Slope ratios of DOC of Greenlandic soils only exhibited significant differences between 4°C and 10°C incubations on the one hand and 15°C on the other hand, at the end of the incubation (Figure 4c). The S_R values of DOC of Greenlandic soils were much higher at the start of the experiment than those of DOC of Siberia but dropped to the same absolute level as the S_R values of Siberian samples at the end of the experiment.

Values for SUVA$_{254}$, an indicator for aromaticity (Weishaar, Aiken et al. 2003), increased over the length of the experiment. For DOC from Greenlandic soils

values increased from 3.5 to 4 at the beginning of the incubation to 7.7 to 9.2 at the end. For DOC from Siberian soils values increased from around 6 to about 10 to 12. The $SUVA_{254}$ values decreased in all DOC samples of the Greenlandic soil between week four and week six while values from all Siberian treatments showed stagnation for this period. The $SUVA_{254}$ values of the DOC of both soils showed an increase from week zero to four and week six to eight. In addition, values of DOC of both soils exhibited the same trend with regard to the different temperature treatments: significant differences could be observed between the 4°C incubations and the 10°C and 15°C incubations.

The Flourescence Index (FI) of the DOC provides an indication of the source of the organic material (McKnight, Boyer et al. 2001).The FI showed a similar trend for both soils and all temperature treatments: it significantly decreased from values between 1.6 and 1.8 at the beginning of the experiment to values between 1.5 and 1.6 at the end of the experiment, suggesting a shift from microbial derived carbon towards organic material derived from humins (Figure 4g, 4h). For both soils FI values were not significantly different for the different temperature treatments at the end of the incubation time. FI values of DOC of Greenlandic soils exhibited significant differences between temperature treatments only between weeks two and four, when values were lowest for the 10°C treatment (Figure 4g). FI values of DOC of Siberian soils showed significant differences from week zero to week six of incubation with smallest values for the 15°C treatment (Figure 4h).

Inoculation experiment

CO$_2$ production

Accumulated CO_2 values showed a linear increase over the time of the inoculation experiment and aquatic microbial communities from Greenland and from Siberia were not significantly different regarding DOC decomposition (Figure 5a, 5c). The quality of the DOC used as substrate had no significant influence on the accumulated CO_2. Microorganisms from Siberian streams showed significantly different CO_2 production for the different DOC qualities only after one week of incubation but not thereafter. Throughout the 28 days of incubation CO_2

production of bacteria incubated with DOC derived from the 15°C treatments was lower than production of bacteria incubated with DOC from 4°C or 10°C treatments. Samples from both soils incubated with DOC derived from incubations at 4°C showed reduction in CO_2 accumulation from day 21 to day 28 (Figure 5a, 5c).

Bacterial densities

Bacterial densities increased over time for aquatic microbial communities from both sampling sites and for all DOC qualities used. Bacterial communities from Siberia showed higher bacterial densities when incubated with DOC derived from the 15°C incubations than Greenlandic communities. There were no significant differences between the communities when incubated with DOC derived from 10°C or 4°C treatments. The samples incubated with DOC from 10°C and 15°C treatments exhibited a stronger increase in bacterial number compared to the samples incubated with DOC from 4°C treatments, despite the fact that we found no differences in respiration rates. At the end of incubation, a statistically significant difference ($p < 0.05$) in bacterial numbers could be observed between samples incubated with DOC derived from incubations at 4°C and incubations at 10°C and 15°C (Figure 5b, 5d).

Discussion

The aim of this study was to analyse the impact of rising temperatures on DOC production and chemical composition of DOC in Arctic soils, as there is evidence for a high amount of potentially decomposable C in these soils (Neff and Hooper 2002). Our results suggest temperature to be a significant factor of DOC production, with higher production rates observed for higher temperature treatments, a finding that is consistent with results from previous temperature incubation experiments (Christ and David 1996; Neff and Hooper 2002; Moore, Pare et al. 2008).

Differences between the soils regarding total SOC and DOC production when normalized to dry weight basis may result from differences between soil and ecosystem type. Whereas Greenlandic soil samples were taken from a typical tundra ecosystem (bioclimate subzone C (Walker, Gould et al. 2002)), Siberian soil samples were taken from a southern tundra site (bioclimate subzone E). Lower summer temperatures and a shorter vegetation period in the typical tundra may have led to lower DOC concentrations of the Greenlandic soils in situ, as vegetation cover was found to be a control on DOC production and export in Arctic tundra ecosystems (Judd and Kling 2002). Since we incubated the soils of the different sites at the same conditions, this cannot apply for the differences that we found in our study. The sites also differed in soil type: in Greenland we sampled a typical gleyic cryosol, while a turbic, histic cryosol was sampled in Siberia, which had much higher carbon content (218 versus 53 mg C g^{-1} dry weight, respectively). Thus, when normalizing DOC production to the soil C content, we could observe that a constant proportion of the total organic SOC was lost as DOC (Figure 1c, 1d).

Higher temperatures are known to increase microbial activity (Christ and David 1996) and thus respiration rates were assumed to rise for the higher incubation temperatures. For the treatments in which respiration rates peaked during the first weeks of incubation, temperature had a stronger affect on CO_2 than on DOC production. Moore, Pare et al. (2008) also found a weaker dependence of DOC

production on temperature and related this to the origin of DOC, which was not only microbial. The CO_2 fraction of the total C loss generally decreased for the higher temperature treatments over the course of incubation, indicating consumption of the most labile DOC substances during the first period of incubation, which might have taken place due to higher microbial activity in these treatments (Figure 2). Other studies (e.g., Fang, Smith et al. 2005; Dutta, Schuur et al. 2006) also reported rapid consumption of labile DOC components during the early stages of their incubation experiments. The decrease of microbial activity during the later period of incubation could reflect the depletion of biodegradable DOC, which was also suggested by DOC quality indicators. Decreasing ratios of DOC absorbance at 250:395nm (E2:E4) and the decreasing Slope ratios (S_R) both suggest a general increase in molecular size of DOC (Figure 4a-4d), as has been also suggested in other studies on DOC composition (Peuravuori and Pihlaja 1997; Helms, Stubbins et al. 2008). The increasing values of the specific UV absorbance ($SUVA_{254}$) (Figure 4c) implied an increase of aromatic, humic compounds in the produced DOC, as has been also found by others (Weishaar, Aiken et al. 2003). Additionally, the temperature sensitivity of microbial metabolism might have changed, a process described as acclimation (Knorr, Prentice et al. 2005) that is consistent with observations of Christ and David (1996), who found microbial communities at earlier stages of incubation to be more sensitive to temperature.

The steady increase in respiration rates at 4°C in Siberian soils and at 10°C in Greenlandic soils indicates a lower microbial activity and therefore a slower consumption of the available assimilable C pool. This is also reflected by the steady increase in CO_2:(DOC+CO_2) ratios of the 10°C incubation of Greenlandic soil, while DOC production for this treatment decreased over time (Figure 1c, 3a, Table 1). Higher E2:E4 and S_R values of DOC from the 4°C incubations than from 10°C and 15°C incubations (especially visible in Siberian DOC samples) also indicate less consumption of labile components during this incubation.

Generally, microbial respiration of Siberian soils showed a stronger response to the temperature treatments than respiration rates of soils from Greenland, which

overall showed less microbial activity. DOC originating from Greenlandic soils showed more pronounced changes in quality at 4°C than at higher temperatures. According to Waldrop, Wickland et al. (2010) reduced temperature sensitivity could either be a result of higher substrate lability or smaller microbial populations. Thus, one explanation could be that the microbial community in the soils from Greenland was smaller compared to those in the soils from Siberia, which is reasonable with regard to the different soil types and climatic conditions. Also, DOC from Greenlandic soils seemed to have more labile components at the beginning of the experiment, with E2:E4 ratios being higher and $SUVA_{254}$ values being lower than in DOC from Siberian soil, which further support the assumptions of Waldrop, Wickland et al. (2010) (Figure 4a-f).

Most of the changes in DOC quality took place during the first two (E2:E4, S_R, FI) or the first four ($SUVA_{254}$) weeks of incubation (Figure 4). This means that most changes in DOC composition took place during this time, which correlates well with the high microbial activity in this period (e.g., respiration rates). However, the changes from week zero to week two of incubation should be considered with care. The Fluorescence Index (FI) suggests a shift in the origin of the DOC (Figure 4g, 4h). Although FI values lie between 1.9 and 1.4, indicating microbial as well as humin sources (McKnight, Boyer et al. 2001), the overall decrease in FI values indicates an increasing importance of DOC derived from humins. The relatively high FI values at the beginning of incubation could have been the result from lysis of microorganisms due to disturbance of the microbial community through establishing the experiment. This might as well be reflected in the high E2:E4 and S_R values and the very low DOC:TDN ratios at the beginning of the incubation experiment (Figure 1g, 1h, Figure 4a-d). Low DOC:TDN ratios suggest dissolved substances with high N content, such as amino-acids that could derive from microbial proteins. Thus, after a short time the microbial community may have assimilated this labile carbon and DOC production from humins and other less labile compounds (aromatic components with generally higher molecular weights) may have started to dominate the DOC quality leading to the observed slower respiration and decomposition rates.

All indicators of DOC quality showed an overall decrease in labile DOC components over the eight weeks of incubation and both soils show less depletion in DOC at 4°C compared to 10°C and 15°C. This proves our hypothesis that higher temperatures lead to an increase in DOC production but to a decrease in DOC quality. The DOC from the 15°C incubations from Siberian soils were most depleted in labile components, reflecting the high production rates observed for this temperature.

The temperature effect on DOC production lasted for a different time period for each of the soils. Whereas DOC production rates in Siberian soils remained more or less constant, DOC production in soil from Greenland declined over time (Figure 1a-d, Table 1). The significant influence of incubation time on DOC production and the resulting decline in production rates in Greenlandic soil could indicate a lower amount of potentially decomposable SOC in the Greenlandic soil, which would fit well to its generally lower C content. Wickland, Neff et al. (2007) found that soils with larger organic C contents also depict larger potential DOC sources. Additionally, organic matter in Greenlandic soil might have been better protected physically or chemically. Studies with longer incubation periods (Dutta, Schuur et al. 2006; Moore, Pare et al. 2008), also found a decline in DOC production over time. One could assume that in Siberian samples the easily decomposable C fraction was not consumed during the relatively short incubation time of this experiment. However, all indicators of DOC quality suggested a change from more labile to more recalcitrant substances in Siberian soil (Figure 4b, 4d, 4f). In addition, respirations rates declined in Siberian soils after an initial peak at 10°C and 15°C (Figure 3b), indicating rapid consumption of labile DOC components, which contradicts the assumption that labile DOC was not consumed. The temperature sensitivity of decomposition of labile and recalcitrant DOC pools might be different as different activation energies for these compounds are needed and kinetic theory suggests a greater temperature sensitivity for the decomposition of recalcitrant substances (Davidson and Janssens 2006). Indicators of DOC quality and a higher total C:N ratio suggested a lower quality of DOC in Siberian soils compared to soils from Greenland already at the beginning of the incubation experiment (Figure 1g-h, Figure 4). This could explain why DOC decomposition seemed to be more temperature

sensitive in Siberian soils. The higher content of aromatic compounds at the end of the experiment suggests a shift in Siberian soils from decomposition of labile to more recalcitrant DOC fractions. If decomposition of this recalcitrant DOC pool had been more temperature sensitive, this could explain why the production rates did not decline in Siberian soils over the course of the incubation.

Differences between the temperature treatments regarding the amount as well as the chemical composition of DOC were significant after eight weeks of incubation. We used this DOC as substrate for a bioavailability experiment. Aquatic microorganisms from Greenlandic streams showed no statistically significant differences in CO_2 production related to DOC composition. Microorganisms from the Siberian streams exhibited lower respiration rates when incubated with DOC derived at 15°C, which was most depleted in labile DOC components (Figure 5c). Maybe a longer incubation time would have increased the differences in DOC composition between the DOC qualities and showed clearer results for the bioavailability experiment.

The reduction in the rate of microbial CO_2 production of samples incubated with DOC derived from 4°C incubations towards the end of the experiment probably occurred because of limitation of easily assimilable carbon due to their lower DOC content. These samples may have become depleted in available substrates for microbial growth earlier than those incubated with DOC leachates of the 10°C and 15°C incubations, which also had higher total DOC contents. This would as well explain the differences in bacterial numbers between the samples incubated with DOC from 10°C or 15°C incubations compared to those of the 4°C incubations at the end of the inoculation experiment (Figure 5b, 5d).

In summary, our study has shown that temperature had a significant influence on DOC production in Arctic soils, both on DOC quantity as well as on DOC quality. This suggests that rising temperatures in the Arctic, as predicted by various studies (ACIA 2005; IPCC 2007), may lead to an increase in the amount of DOC leached from Arctic soils, whereas the availability of this DOC is likely to decrease. These changes might affect the C cycling in the Arctic as a whole. However, our study did not show clear results concerning the fate of DOC in

Arctic streams and no experiments were conducted to evaluate the impacts of changes in DOC composition on the C cycling in the Arctic Ocean.

Figures and Tables:
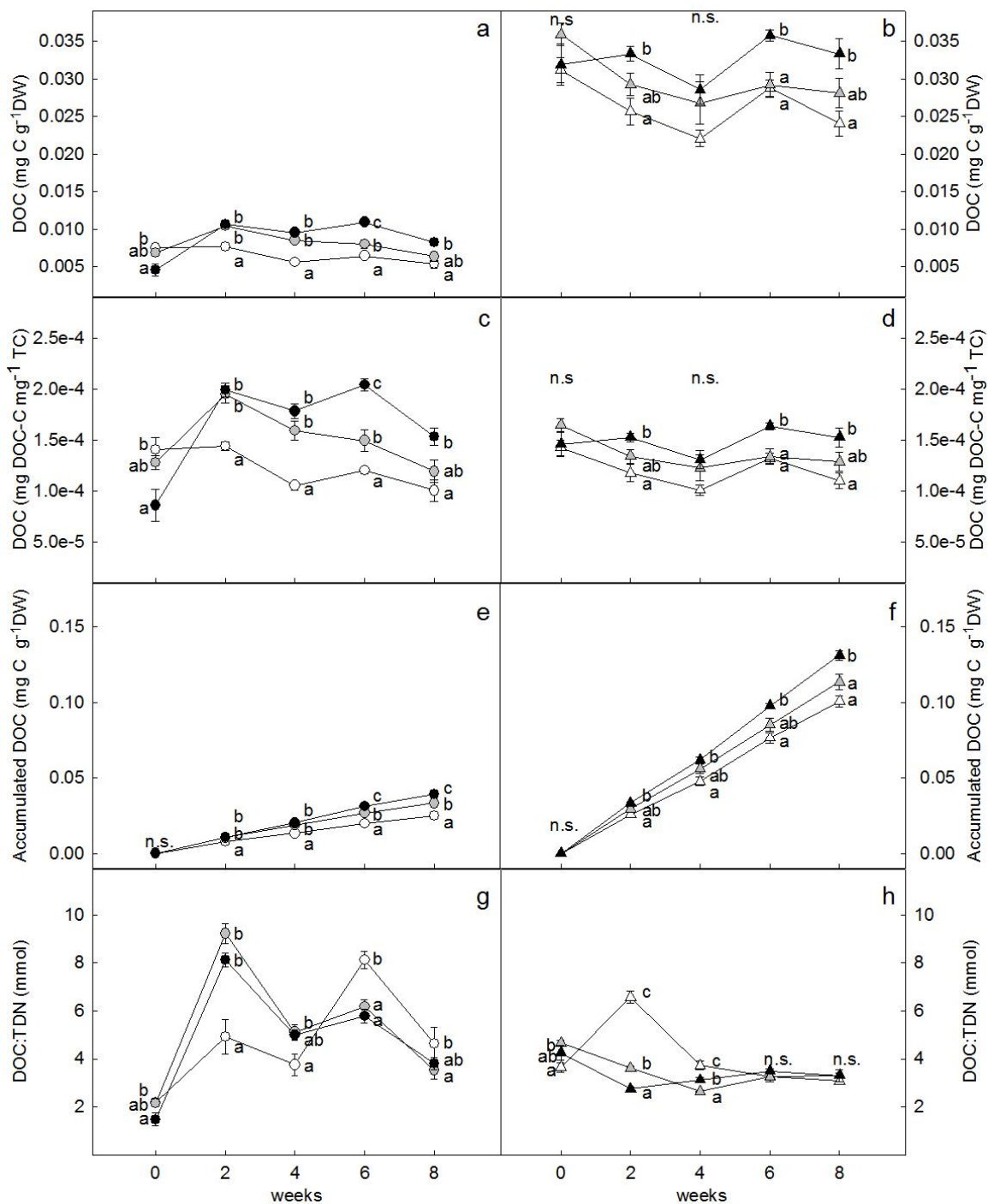
Figure 1. DOC production on a dry weight basis (a, b) and per unit of carbon (c, d), accumulated DOC production (e, f) and DOC:TDN ratios (g, h) in soils from Greenland (left panels; circles) and Siberia (right panels, triangles); different letters show significant differences between the temperature treatments for each time point (n.s. = not significant). Open symbols, incubations at 4°C; grey symbols, incubations at 10°C; black symbols, incubations at 15°C.
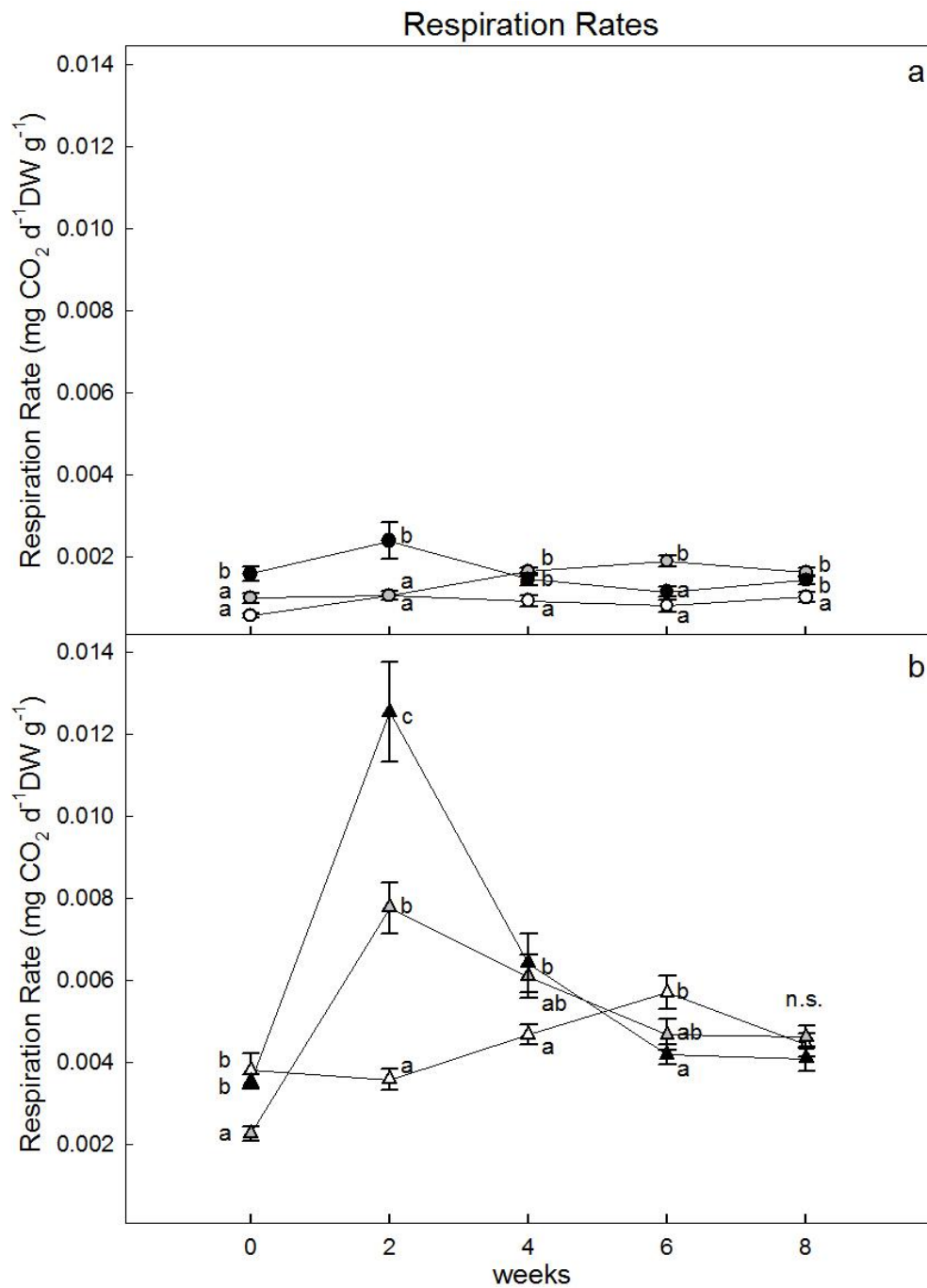
Figure 2. Respiration rates during eight weeks of incubation for soils of Greenland (a) and Siberia (b); different letters show significant differences between the temperature treatments for each time point (n.s.=not significant). Open symbols, incubations at 4°C; grey symbols, incubations at 10°C; black symbols, incubations at 15°C.
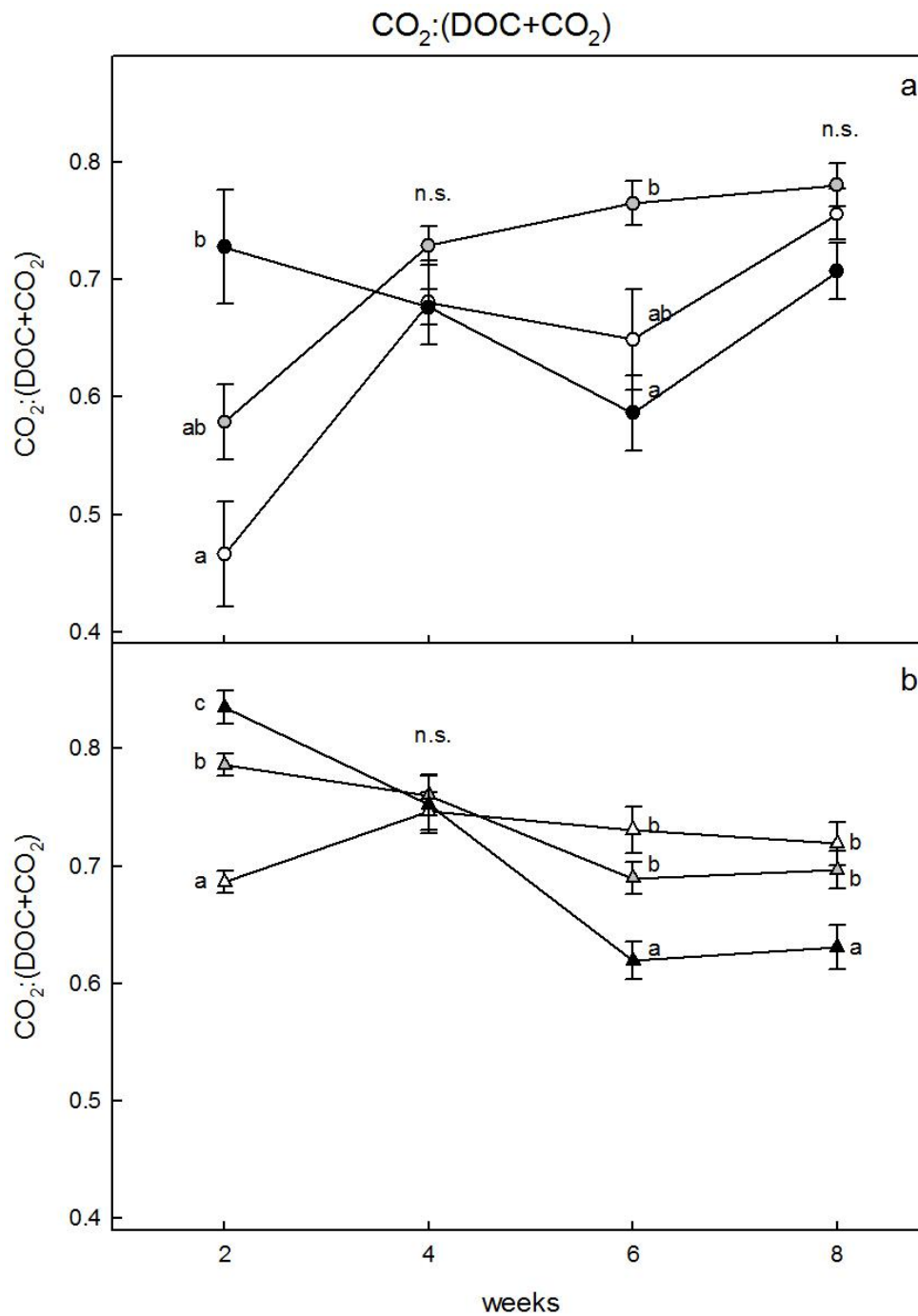
Figure 3. CO_2:($DOC+CO_2$) ratios for soils of Greenland (a) and Siberia (b); different letters show significant differences between the temperature-treatments for each time point (n.s.=not significant). Open symbols, incubations at 4°C; grey symbols, incubations at 10°C; black symbols, incubations at 15°C.
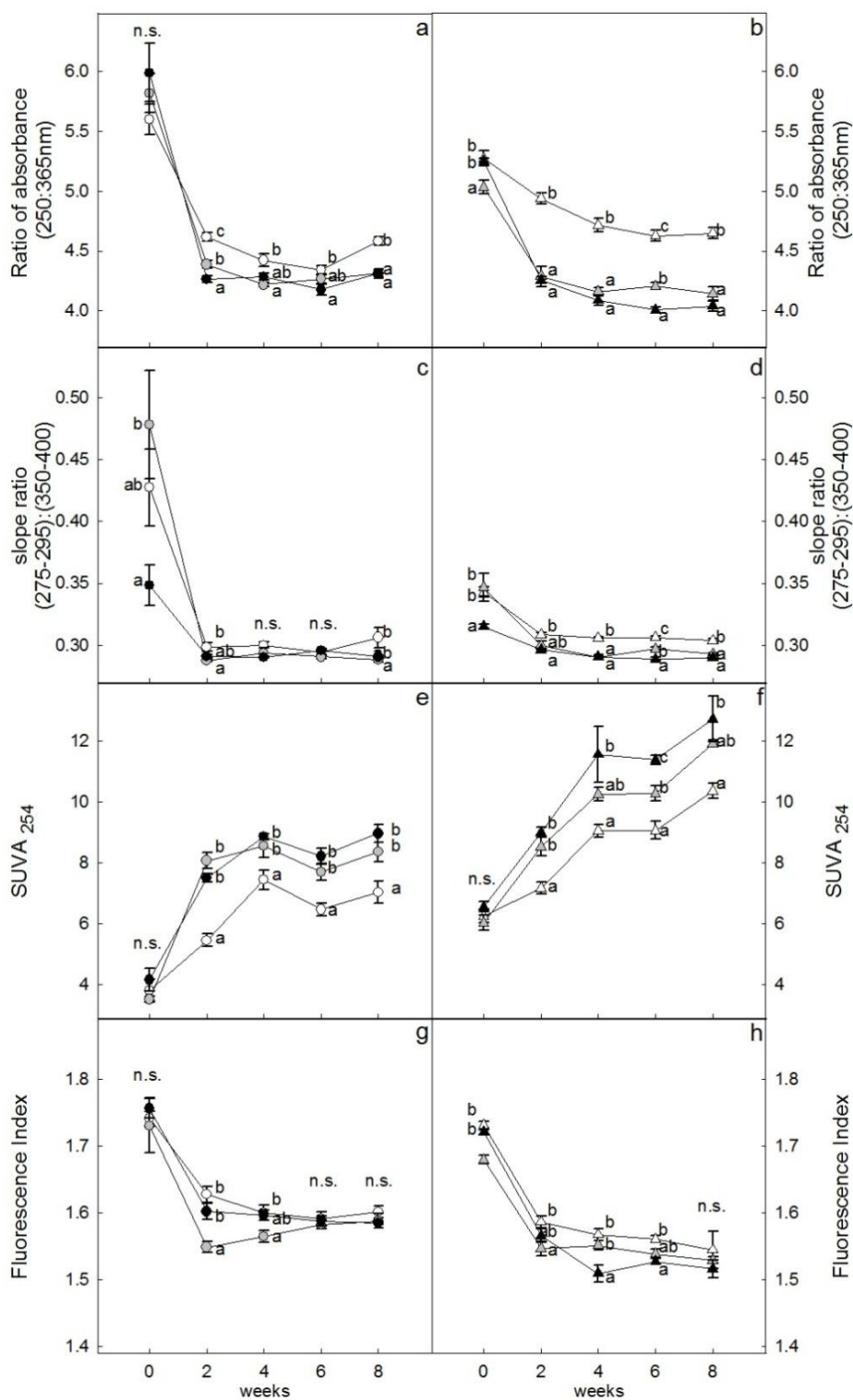
Figure 4. Changes in DOC quality over eight weeks of incubation. Ratio a250:a365 for soils of Greenland (a) and Siberia (b); Slope ratios for soils of Greenland (c) and Siberia (d); SUVA$_{254}$ for soils of Greenland (e) and Siberia (f); FI for soils of Greenland (g) and Siberia (h). Different letters show significant differences between the temperature treatments for each time point (n.s.=not significant). Open symbols, incubations at 4°C; grey symbols, incubations at 10°C; black symbols, incubations at 15°C

Figure 5. Accumulated CO_2 production of the inoculation experiment for soils of Greenland (a) and Siberia (c) and bacterial densities at 28 days after inoculation for microbial communities from Greenland (b) and Siberia (d); different letters show significant differences between the temperature treatments for each time point (n.s.=not significant). Open symbols, incubations at 4°C; grey symbols, incubations at 10°C; black symbols, incubations at 15°C.
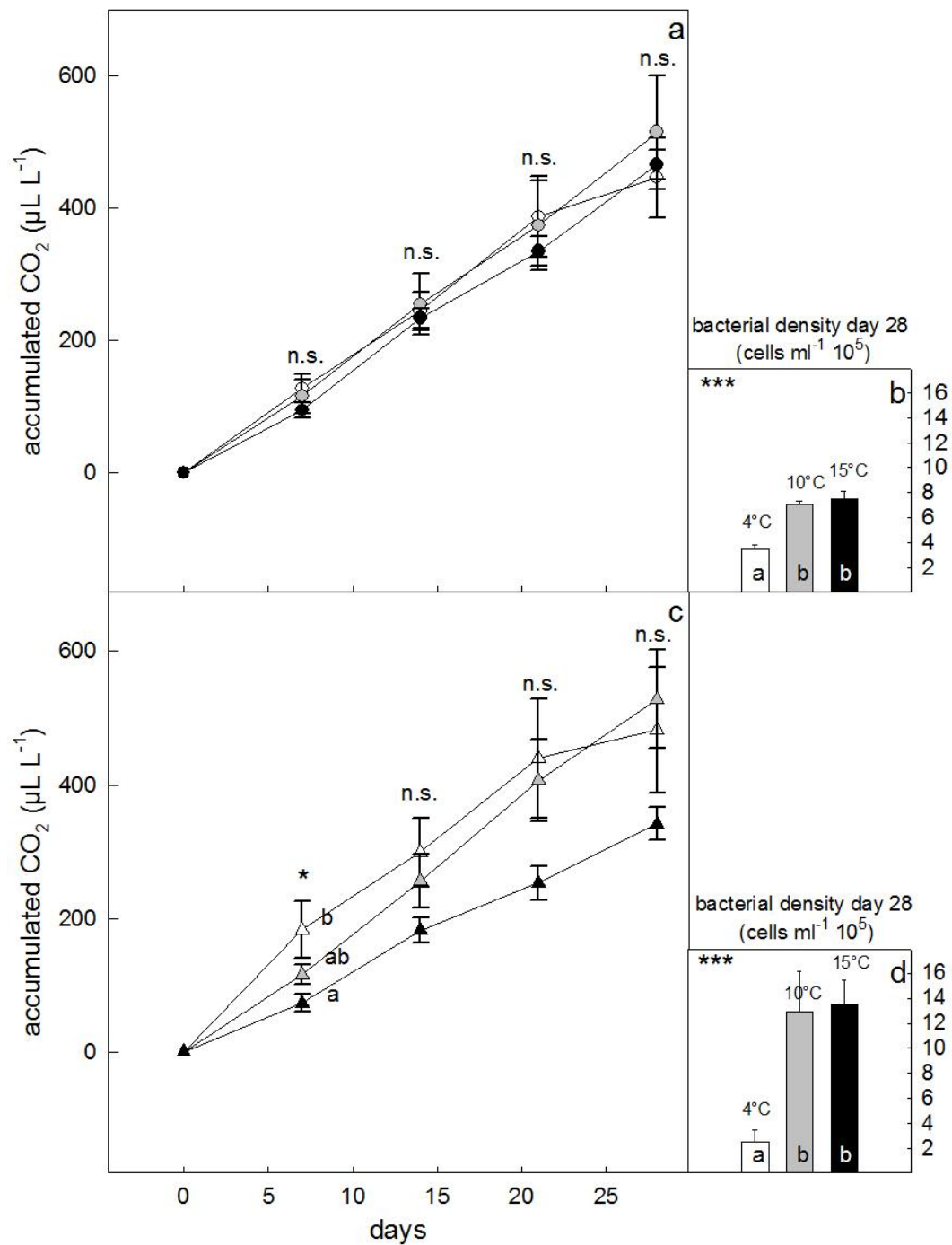
Table 1. Variation of DOC production over eight weeks of incubation, letters indicate differences between the weeks n.s.=not significant, * = p<0.05, ** = p<0.01, *** = p<0.001

Greenland

weeks	0	2	4	6	8	F-ratio	p-value
4°C	B	B	A	AB	A	6.68	***
10°C	AB	C	BC	AB	A	10.15	***
15°C	A	C	BC	C	B	26.4	***

Siberia

weeks	0	2	4	6	8	F-ratio	p-value
4°C	C	ABC	A	BC	AB	6.03	*
10°C	B	AB	A	AB	AB	3.24	*
15°C	A	A	A	A	A	2.09	n.s.

Table 2. Variation of CO2: (DOC+CO2) production over eight weeks of incubation, letters indicate differences between the weeks n.s. = not significant, * = p<0.05, ** = p<0.01, *** = p<0.001

Greenland

weeks	2	4	6	8	F-ratio	p-value
4°C	A	B	B	B	10.59	***
10°C	A	B	B	B	17.03	***
15°C	B	AB	A	AB	3.37	*

Siberia

weeks	2	4	6	8	F-ratio	p-value
4°C	A	A	A	A	2.18	n.s
10°C	B	B	A	A	11.02	***
15°C	C	B	A	A	29.23	***

Table 3. Total C, N and C:N (molar) for soils from Greenland and Siberia

Soil	mg C g^{-1}soil		mg N g^{-1}soil		C:N (molar)
	average	SE	average	SE	
Greenland	53.5	2.93	3.14	0.16	19.9
Siberia	218.6	10.48	9.32	0.34	27.4

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Zusammenfassung

Permafrostböden speichern große Menge an Kohlenstoff, da die kalten und feuchten Bedingungen in der Arktis die Abbauprozesse von organischem Material in Böden in der Vergangenheit stärker verlangsamt haben als den Aufbau von Biomasse. Diese Kohlenstoffspeicher sind jedoch durch den Klimawandel gefährdet, da höhere Temperaturen zum Auftauen von Permafrost führen und die Abbaubedingungen damit begünstigen könnten. So könnte etwa durch erhöhte mikrobielle Atmung mehr CO_2 in die Atmosphäre gelangen und zu einer positiven Rückkoppelung auf den Klimawandel führen.

Mikroorganismen nehmen primär gelösten organische Kohlenstoff (dissolved organic carbon, DOC) auf, weshalb dieser Fraktion des organischen Kohlenstoffs in den Permafrostböden eine besondere Bedeutung zukommt. DOC besteht aus verschiedenen Substanzen unterschiedlichen Molekulargewichts, die daher unterschiedlich leicht für Mikroorganismen zu verwerten sind.

Die vorliegende Arbeit untersuchte, inwiefern sich Produktion und chemische Zusammensetzung des DOCs unter erhöhten Temperaturen ändern und welche Auswirkungen dies auf seine Abbaubarkeit durch aquatische Mikroorganismen hat. Wir stellten die Hypothese auf, dass erhöhte Temperaturen zwar die Menge des produzierten DOCs erhöhen, jedoch seine Qualität, also die Abbaubarkeit, verringern würde. In einem ersten Experiment wurden Tundraböden aus Grönland und Sibirien bei drei verschiedenen Temperaturen (4°C, 10°C, 15°C) inkubiert und die DOC-Produktion über acht Wochen verfolgt. In einem zweiten Experiment wurde die Abbaubarkeit dieses DOCs getestet. Mikrobielle Gemeinschaften aus grönländischen und sibirischen Flüssen erhielten DOC aus dem ersten Experiment, der bei unterschiedlichen Temperaturen produziert wurde, als Substrat. Die mikrobielle Aktivität wurde in beiden Versuchen mittels CO_2-Produktion gemessen.

Temperatur erwies sich als entscheidender Faktor für mikrobielle Aktivität und DOC-Produktion. In beiden Böden war die DOC-Produktion in den Inkubationen

bei 15°C am höchsten. Die Böden unterschieden sich stark hinsichtlich ihres Kohlenstoffgehaltes, der Anteil des ausgewaschenen DOCs zum Gesamtkohlenstoffgehalt war jedoch ähnlich. Die Qualität des DOCs verringerte sich über die Inkubationszeit, wobei in den Inkubationen bei 15°C die höchste Anreicherung von höhermolekularen, rekalzitranten Substanzen zu beobachten war, während die Inkubationen bei 4°C am meisten labile Substanze aufwiesen. Der Inokulationsversuch zeigte für die Proben aus Sibirien einen schwachen Trend: Proben, die mit DOC aus den Inkubationen bei 15°C versetzt wurden, produzierten weniger CO_2.

Die Ergebnisse der vorliegenden Studie deuten darauf hin, dass durch die steigenden Temperaturen in der Arktis zukünftig mehr DOC aus den Permafrostböden ausgewaschen werden könnte. Dieser DOC wird jedoch mehr höhermolekulare, rekalzitrante Substanzen enthalten und daher schlechter abbaubar sein.

Curriculum vitae

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