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Micro-topographic patterns unravel controls of soil water and temperature on soil respiration in three Siberian tundra systems

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A B S T R A C T

Spatial and temporal patterns of soil respiration rates and controlling factors were investigated in three wet arctic tundra systems. *In situ* summer season carbon dioxide fluxes were measured across a range of micro-topographic positions in tussock tundra, wet sedge tundra, and low-centre polygonal tundra, at two different latitudes on the Taimyr Peninsular, central Siberia. Measurements were carried out by means of a multi-channel gas exchange system operating in continuous-flow mode.

Measured soil respiration rates ranged from 0.1 g CO_2-C m^{-2} d^{-1} to 3.9 g CO_2-C m^{-2} d^{-1} and rate differences between neighbouring sites in the micro-topography (microsites) were larger than those observed between different tundra systems. Statistical analysis identified position of the water table and soil temperature at shallow depths to be common controls of soil respiration rates across all microsites, with each of these two factors explaining high proportions of the observed variations.

Modelling of the response of soil respiration to soil temperature and water table for individual microsites revealed systematic differences in the response to the controlling factors between wet and drier microsites. Wet microsites – with a water table position close to the soil surface during most of the summer – showed large soil respiration rate changes with fluctuations of the water table compared to drier microsites. Wet microsites also showed consistently higher temperature sensitivity and a steeper increase of temperature sensitivity with decreasing temperatures than drier sites. Overall, Q_{10} values ranged from 1.2 to 3.4. The concept of substrate availability for determining temperature sensitivity is applied to reconcile these systematic differences. The results highlight that soil respiration rates in wet tundra are foremost controlled by water table and only secondarily by soil temperature. Wet sites have a larger potential for changes in soil respiration rates under changing environmental conditions, compared to drier sites.

It is concluded that understanding and forecasting gaseous carbon losses from arctic tundra soils and its implication for ecosystem-scale CO_2 fluxes and soil organic matter dynamics require good knowledge about temporal and spatial patterns of soil water conditions. The water status of tundra soils can serve as a control on the temperature sensitivity of soil respiration.

1. Introduction

The Arctic has warmed by about 2 °C over the last three decades, and Global Circulation Models predict that arctic tundra will continue to experience some of the strongest climatic changes following global warming (ACIA, 2005; IPCC, 2007). The amount of carbon present in arctic soils is approximately half of that in the entire atmosphere (Raich and Schlesinger, 1992), and thus an increased release of CO_2 from tundra soils would result in significant positive feedback to global warming (Gorham, 1991; Schlesinger and Andrews, 2000). Soil respiration, the CO_2 flux measured at the interface of the soil and the atmosphere and deriving from root, rhizome, and microbial respiration, represents the dominant export of carbon from soils. Comprehension of the factors controlling soil respiration is thus essential for understanding the dynamics of carbon exchange between tundra ecosystems and the atmosphere.

A closer look at the arctic landscape, however, reveals a very rich mosaic of topography, soils and vegetation types, and frost patterns, on spatial scales ranging from centimetres to kilometres. Conditions known to exert strong control over soil respiration, such as soil temperature, water table position, thaw depth, and organic matter quality, show pronounced differences across each of these scales (Flanagan and Veum, 1974; Peterson and Billings, 1975; Moore and Knowles, 1989; McKane et al., 1997). In a meta-analysis of the response of soil respiration to warming experiments, Rustad et al. (2001) stressed that only a thorough understanding of the relative

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importance of the controlling factors on each spatial and temporal scale can lead to a reasonable base for scaling up from plot and site to landscape or biome levels. Similarly, the interpretation of net ecosystem CO_2 fluxes derived from eddy covariance measurements requires detailed knowledge about the spatial distribution of surface types and their specific CO_2 fluxes (Oechel et al., 1998), which is often limited by knowledge of ecosystem respiration (Nordstroem et al., 2001), with soil respiration being a dominant part thereof in tundra ecosystems (Sommerkorn et al., 1999). This paper makes a contribution to the understanding of the spatial variability of soil respiration rates in wet and moist tundra in central Siberia, a region where limited data exist. The study identifies as well as quantifies common controlling factors for soil respiration in a form capable for implementation into ecosystem models and for interpretation of eddy covariance measurements.

Because soil respiration is a physiologically heterogeneous process (i.e. the respired carbon derives from a range of different biochemical substrates, pathways, and organisms) and the respired CO_2 can originate from different soil depths, it is still actively debated which factors serve best to describe the process (e.g. Oberbauer et al, 1991; Lloyd and Taylor, 1994; Buchmann, 2000; Davidson and Janssens, 2006). Soil respiration measured *in situ* across temporal and spatial scales provides a direct way to identify controlling factors and assess their relative importance because a functionally integrated soil system is maintained. This is of particular importance for the characterisation of the temperature sensitivity of soil respiration because measuring *in situ* avoids artificial intrinsic temperature sensitivities caused by a disturbed substrate suite, and can also unravel possible effects of environmental constraints on the apparent temperature sensitivity (Davidson and Janssens, 2006). Because gradual shifts of ecosystem structure and function in response to climate change will occur along the same axes as existing patterns and gradients (Tenhunen et al., 1992), such an approach can also serve to identify trajectories of gaseous carbon export from wet and moist tundra soils with altered climate forcing. Another goal of this study is therefore to gain a process-level understanding of factors controlling *in situ* soil respiration in wet and moist tundra systems. Using a combination of *in situ* measurements and regression modelling the study identifies differences in respiration rates as well as in the response to common controlling factors. It also seeks to identify further site-specific controlling factors by interpreting systematic differences in the modelled response surfaces and discussing site characteristics responsible for these differences. To achieve this, a continuous-flow gas exchange system is used that allows continuous and high time-resolution measurements of soil respiration, at the range of micro-topography (microsites) present in a tundra system, over extended periods of the growing season. Regression modelling is then used to (i) interpolate respiration rates through the growing season, (ii) identify the response surfaces of controlling factors, (iii) quantify between-microsite differences in the response to controlling factors, and (iv) link patterns emerging from those differences to microsite characteristics.

2. Materials and methods

2.1. Study region

Taimyr Peninsula, situated in northern central Siberia, covers an area of about 400,000 km^2 between 70°N and 78°N, and 86°E and 115°E. The region is characterized by a continuum of climatologically determined vegetation units from the Taiga to the Polar Desert, covering Southern Arctic Tundra, Typical Arctic Tundra, and Northern Arctic Tundra (Aleksandrova, 1980; Walter and Breckle, 1986; Matveyeva, 1994). Taimyr Peninsula's climate is cold–dry–continental with a mean annual temperature of about −13 °C, and the entire region is underlain by permafrost. The number of days above 0 °C differ across Taimyr Peninsula, with 40–50 days in the South and 20–30 days in the North (Matveyeva, 1994). Annual precipitation decreases from 350 mm in the southwest to 250 mm in the southeast (Norin and Ignatenko, 1975).

2.2. Study sites

The study was conducted at two intensive study sites, approximately 250 km apart. The southern site "Lake Labaz" is situated at 72°23′N, 99°43′E in the North Siberian Lowland and inside the vegetation zone of the Southern Arctic Tundra, at about 50 m a.s.l. At the nearest climate station in Khatanga, about 100 km to the East, the mean July air temperature is 13.8 °C and annual precipitation averages 243 mm. The predominant gley soils of the study area are derived from clayey to loamy parent material. They are characterized by high water content, low thaw depth (i.e. <60 cm), a pergelic temperature regime and organic layers up to 30 cm in thickness. The extensive levelled and therefore wet soils representing most of the study area are Ruptic Histoturbels (Gundelwein et al., 2007). They are covered by tussock tundra dominated by *Eriophorum vaginatum*, subarctic dwarf-shrubs, as well as mosses like *Tomentypnum nitens* and *Hylocomium splendens*. Vascular plant biomass is 225 g DW m^{-2} (Sommerkorn, 1998). On entirely flat areas with water tables at the soil surface the soils are Typic Aquorthels with no patterned ground structure. In these areas a wet sedge tundra with a vascular plant biomass of 177 g DW m^{-2} is established. The vegetation is dominated by *Carex stans* and *Eriophorum angustifolium* as well as the moss *Drepanocladus uncinatus* (Siegert and Bolshiyanov, 1995).

Soil respiration measurements were carried out at three locations in the micro-topography ("microsites") of tussock tundra, situated approximately 1 m apart from each other, on a tussock (TT), a moss hummock (TH, a late-succession tussock that is broadened but still elevated and on which the dominant vegetation has changed from *E. vaginatum* to mosses) and in the inter-tussock depression (TD), and also in wet sedge tundra (WS) that showed no micro-topography. Measurements were carried out between 26 July and 19 August 1995.

The northern study site "Lake Levinson-Lessing" is situated at 74°32′N, 98°36′E in a valley of the western part of the Byrranga Mountains inside the vegetation zone of the Typical Arctic Tundra, at 40 m a.s.l. Surrounding mountains reach heights of up to 560 m. The nearest climate station, Taimyr Lake Station, about 70 km to the East, records a mean July air temperature of 6.6 °C and an annual precipitation of 281 mm. At the study site, the soils of the valley are derived from loamy to sandy sediments of fluvial origin. They show a pergelic temperature regime and an aquic soil moisture regime. Organic layers of weakly decomposed organic material are up to 10 cm thick and maximum active layer depths do not exceed 30–45 cm. In the extensive levelled areas of the valley polygonal structures, mainly low-centre-polygons are developed. The diameter of the polygons ranges from 6 to 12 m and the apices with underlying ice-wedges are 10–60 cm high. The soils are classified as Typic Psammorthels (Melles et al., 1997; Soil Survey Staff, 1999). The central wet depressions are dominated by *C. stans* and *Dupontia fisheri*, as well as *Drepanocladus revolvens*. The apices with the underlying ice-wedges are covered by dwarf-shrubs like *Dryas punctata* and a dense moss carpet dominated by *T. nitens* (Sommerkorn, 1998). Vascular plant biomass in this tundra is 56 g DW m^{-2}.

Soil respiration was measured at three microsites along a micro-topo-sequence of approximately 3 m length, a high apex (PH), a low apex (PL) and the polygon centre (PD), between 23 July and 8 August 1996.