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Thawing sub-arctic permafrost: Effects on vegetation and methane emissions

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[1] Ecosystems along the 0°C mean annual isotherm are arguably among the most sensitive to changing climate and mires in these regions emit significant amounts of the important greenhouse gas methane (CH_4) to the atmosphere. These CH_4 emissions are intimately related to temperature and hydrology, and alterations in permafrost coverage, which affect both of those, could have dramatic impacts on the emissions. Using a variety of data and information sources from the same region in subarctic Sweden we show that mire ecosystems are subject to dramatic recent changes in the distribution of permafrost and vegetation. These changes are most likely caused by a warming, which has been observed during recent decades. A detailed study of one mire show that the permafrost and vegetation changes have been associated with increases in landscape scale CH_4 emissions in the range of 22–66% over the period 1970 to 2000. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); 1832 Hydrology: Groundwater transport; 1890 Hydrology: Wetlands. **Citation:** Christensen, T. R., T. Johansson, H. J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson (2004), Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, *Geophys. Res. Lett.*, *31*, L04501, doi:10.1029/2003GL018680.

1. Introduction

[2] Effects of climate change on ecosystem functioning are likely to be most pronounced in regions where major disruptions to ecosystem structure should be expected within the range of a few degree change in mean annual temperature. A pronounced example of such regions is the subarctic terrestrial environments that are in part underlain by permafrost. The presence or absence of permafrost provides major variations in the physical soil foundation. It determines the surface micro-topography, which in turn determines the plant community structure and its productivity. It also, to a large extent, determines the hydrological and nutritional status of the soil conditions which are pivotal for the vegetation distribution and for important functional aspects such as the ecosystem carbon balance and emissions of greenhouse gases most notably CH_4.

[3] CH_4 is an important and strong greenhouse gas with natural emissions comprising 40% of the total global estimate with wetlands representing the majority [*IPCC*, 2001]. These emissions are temperature sensitive [*Christensen et al.*, 2003; *Crill et al.*, 1992] and could provide significant feedback mechanisms in a changing climate.

2. Study Site, Permafrost and Climate

[4] This study was conducted in the Abisko region (68°22'N, 19°03'E) in subarctic Sweden. The subjects of study were several bogs or mixed mires underlain by permafrost. The intensive study site, Stordalen, is situated 12 km east of Abisko. The long-term climate record obtained at Abisko Scientific Research Station shows significant variability around a long-term (1913–2002) mean annual temperature of −0.7°C (Figure 1). Two periods of warming (1915–1933 and 1975–2002) are separated by a period in the middle with decreasing temperatures. The summer temperatures quantified as growing degree-days above zero have been found in the Abisko region as the best predictor of the general active layer depth in places where permafrost is still present [*Brown et al.*, 2000]. The warming trend over the past decades has been found to be associated with complete disappearance of permafrost in certain mires. In Figure 1 we show the mean active layer depth observed at eight different mire sites in the Abisko region plotted together with the mean summer temperature for the period 1978–2002. The average warming of more than 1°C observed since the early 80s is coincident with an increase in the mean active layer depth,

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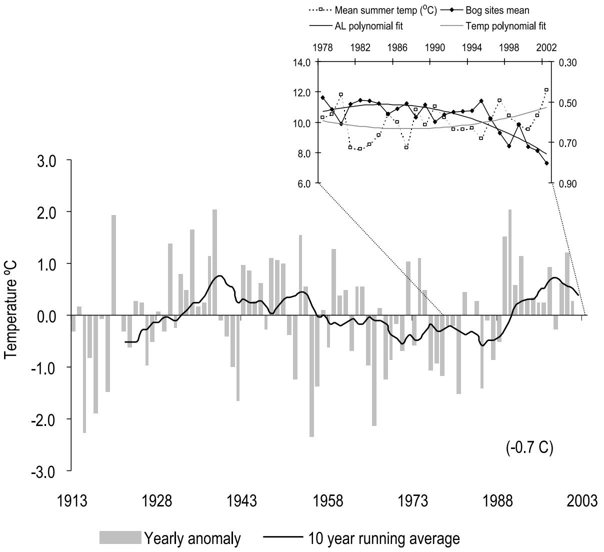

Figure 1. Main: The mean annual temperature anomalies (bars) at Abisko since the start of the recording in 1913 around the mean annual temperature for the same period of −0.7°C. The line indicates a ten-year moving average. Insert: Mean summer temperature at Abisko (first y-axis) together with the mean maximum active layer (AL) depth at eight mire sites in the area (second y-axis). Note the scale of the second y-axis is reversed and indicates with increasing depth the increasing seasonal thaw depth. The polynomial fits are illustrating the tendency for the two curves to mirror each other with only the temperature fit being statistically significant.

which has deepened by more than 20 cm over the same period (Figure 1).

3. Methods

[5] The vegetation-type specific CH_4 flux measurements were carried out using standard closed chamber techniques [*Bellisario et al.*, 1999; *Bubier et al.*, 1999; *Bubier et al.*, 1995; *Christensen et al.*, 2000; *Joabsson and Christensen*, 2001] with CH_4 analysis carried out on gas chromatographs equipped with a FID sensor at the Abisko Scientific Research Station. The automatic chambers [*Goulden and Crill*, 1997; *Goulden et al.*, 1998] (three-hour measurement cycle) used a Li-Cor 6262 for CO_2 analyses and a California Instruments Total Hydrocarbon (THC) Analyser for measurements of THC flux. The THC fluxes were determined to be >95% CH_4 by grabsampling and subsequent GC-FID analysis.

[6] The eddy correlation measurements were carried out using a 3 meter mast equipped with a 3-D sonic anemometer (Gill) and a tuneable diode laser (Aerodyne Inc., USA) for CH_4 measurements. Previous use of the same system has been documented earlier applied at this same study site [*Friborg et al.*, 1997], in NE Greenland [*Friborg et al.*, 2000] and in Siberia [*Friborg et al.*, 2003].

[7] Two sets of aerial photographs taken of the intensive study site, Stordalen, with infrared color film were used for the classification. One from 1970 taken in the beginning of August at a height of 1500 m and one from the beginning of July 2000 taken at a height of 4600 m. To make the two aerial photographs comparable the 1970 picture was resampled to a 1-meter pixel size and registered to the Swedish grid (RT 90) by using the 2000 image as geocoded target image. The higher resolution photograph was degraded to match the lower resolution. The 2000 photograph was orthogonal prerectified to the Swedish grid by the Swedish National Land Survey. The vegetation maps were made with a combination of manual interpretation and supervised Maximum likelihood classification made in PCI Geomatica V8.2 (PCI Geomatics). The map recording the change between 1970 and 2000 was performed using Idrisi32 (Clark Labs).

[8] The climate data presented are derived from the Nordklim ver. 1.0 dataset and the Abisko Scientific Research Stations own observations. The active layer depth monitoring was done by surveying a representative area of eight different mires in the region (third week of September each year). The vegetation survey of Stordalen in 2000 was carried out by Nils and Tomas Malmer.

4. Results and Discussion

[9] Based on visual observations in most of the mires the increasing active layer depth has been associated with generally wetter soil conditions. In one mire, Katterjokk the permafrost has disappeared altogether over the period 1998–2002 and the vegetation has shifted from shrub-dominated, elevated, ombrotrophic conditions to wet graminoid dominated more nutrient rich or minerotrophic conditions [*Åkerman et al.* (in prep.) and http://www.geography.uc.edu/~kenhinke/CALM]. The changes at the intensive study site in the present study, the Stordalen mire (68°22’N, 19°03’E), have been less dramatic but show the same trend. Stordalen is a unique site for the comparison of possible vegetation changes at the decadal timescale as it was intensively surveyed during the International Biological Program (IBP) in the early 70s [*Sonesson*, 1980]. We divided the mire into four vegetation categories comparable to information from plant community surveys made in 1970–74. A classification of the entire mire based on infrared airborne images is adapted to quantify the aerial extent of the individual vegetation types (Table 1). This classification was validated against a detailed vegetation survey made in the summer of 2000. We found about 80% correspondence between the 1505 plots identified and the classification based on the airborne infrared image shown in Figure 2b [*Malmer et al.* in prep.]. Table 1 shows the areal distribution of the different vegetation types in 2000 versus a similar estimate based on a comparable airborne image from 1970. The vegetation composition has changed significantly with a decrease in the permafrost-dependent relatively dry elevated mire vegetation types and a corresponding increase in the lower wet graminoid dominated vegetation. This change corresponds with changes in the underlying permafrost distribution as the latter is determining the mire surface topography and hydrology, and hence the plant community structure.

[10] The Stordalen mire represents one of the most well documented mires in the world with respect to data on CH_4 fluxes from individual vegetation types. The first measurements of CH_4 emissions were made during the IBP [*Sonesson*, 1980; *Svensson and Rosswall*, 1984] and since

Table 1. Summary of Six Different Vegetation Types in the Stordalen Mire, Their Estimated CH_4 Fluxes and Areal Coverage in 1970 Versus 2000

	Flux range (mean estimate) ($mg\ CH_4/m^2/hr$)	Areal coverage (hectares)		Flux change 1970–2000 ($g\ CH_4/hr$)	Δflux (%)
Year		1970	2000		
Total area		50.3	49.0		
Dry ombro*	-0.07–0.07 (−0.02)	9.2	5.9	+6.7[a]	36
Semiwet ombro*	0.12–2.8 (2)	2.1	2.7	+10.8	25
Wet ombro*	1–7.5 (5)	4.0	6.7	+137.8	69
Minero*	3.2–18 (12)	0.5	0.65	+11.0	17
Open water	−(0.004)	24.4	25.6	+0.5	5
Pavement	0	0.009	0.003	0	0

All mire	1970 ($mg\ CH_4/m^2/hr$)	2000 ($mg\ CH_4/m^2/hr$)	% change
Areally weighted flux	1.8–2.2	2.7–3.0	22–66

Vegetation groups (*) correspond to detailed descriptions in *Svensson et al.* [1999] with some modifications in Malmer et al. [in prep.]. Flux estimates are based on a range of published [*Christensen et al.*, 2003; *Öquist and Svensson*, 2002; *Svensson*, 1980; *Svensson et al.*, 1999] and soon to be published numbers [*Nikpur et al.*, unpublished; *Crill et al.*, in prep.; *Christensen et al.* in prep.].

then several campaigns have provided comparable data [*Öquist and Svensson*, 2002; *Svensson et al.*, 1999]. Recent automated chamber flux measurements in three of the major vegetation units have confirmed the flux rates in Table 1. All these flux studies, in particular *Svensson et al.* [1999], demonstrate that the individual vegetation communities are relatively robust in their correspondence with CH_4 emissions when normalized to climatic factors particularly temperature and moisture. This means that a shift in habitats and hence vegetation composition alone indicate a predictable change in the range of CH_4 emissions.

[11] We have also conducted landscape scale eddy correlation measurements of CH_4 emissions on a campaign basis in the Stordalen mire during the period 1996–2002. We have in total 2 months of high time-resolution measurements of CH_4 emissions over the mire of which 50% is from the growing season. An average summer flux derived from these measurements amount to $3.08 \pm 0.15\ mg\ CH_4/m^2/hr$. Extrapolating the terrestrial surfaces from the chamber measurements in Table 1 the areally weighted mean summer CH_4 flux for the current vegetation distribution is in the range $2.7–3.0\ mg\ CH_4/m^2/hr$. The vegetation based extrapolation of chamber measurements and the landscape scale eddy correlation measurements are, hence, in accordance.

[12] Aerial infrared images were then used to compare the relative distribution between 1970 and 2000 of the vegetation types with respect to CH_4 emissions. Figure 2a and 2b shows the distribution of elevated ombrotrophic and wet vegetation types on the mire in 1970 and 2000 respectively. It is clear from this figure that the wet or semiwet categories have all increased in size on the costs of the dry elevated areas. The latter, permafrost-dependent, vegetation type appears to be fragmenting.

[13] Applying the mean chamber flux rates for the individual vegetation types in the years around 2000 we derive an estimate of how vegetation attributed changes have altered the landscape scale CH_4 emissions (Figure 3 and Table 1). Following this analysis the microtopographical and hydrological changes as indicated by vegetation change alone turns out to have caused an increase in the landscape scale CH_4 emissions from 1970 to 2000 ranging between 22 and 66%.

[14] Recent observations of permafrost degration in subarctic Alaska [*Jorgenson et al.*, 2001] and Canada [*Turetsky et al.*, 2002] confirm the trend toward the ecosystems getting wetter as a consequence of permafrost disappearance, as we also have observed. In the Arctic proper with continuous permafrost, initial warming, that does not extent to permafrost disappearance, may have other and possibly opposite effects if surface soil drying occurs. There is evidence from northern Alaska that this may already be the case in response to warming during recent decades [*Oechel et al.*, 2000]. In a global context this points to the importance of regional variations in responses to changes in climate and that subarctic and arctic terrestrial areas might

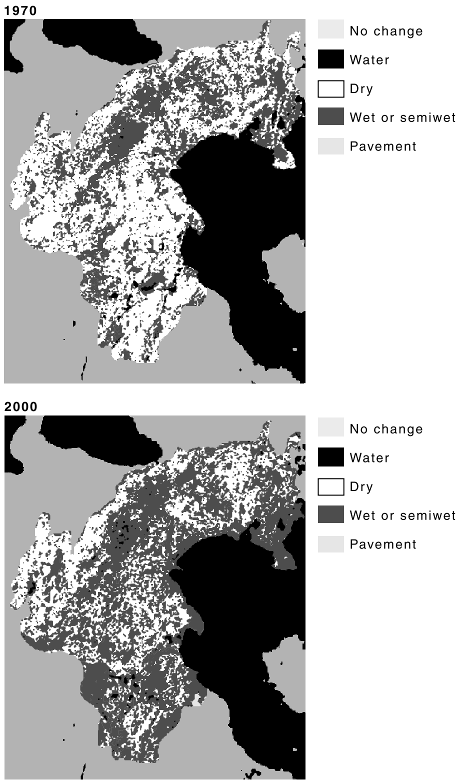

Figure 2. Vegetation distribution as classified based on infrared aerial photographs in (a) 1970 and (b) 2000. NC: not classified. See color version of this figure in the HTML.

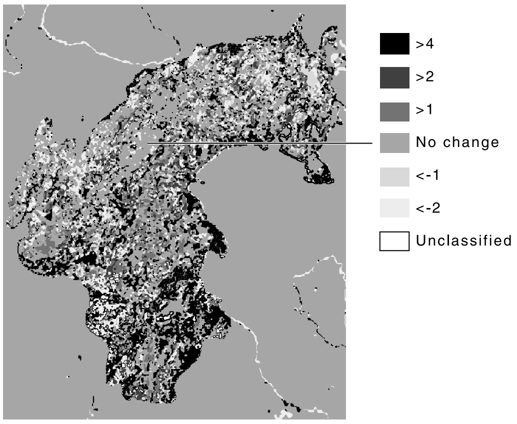

Figure 3. Vegetation derived changes in mean summer CH_4 emissions (mg $CH_4/m^2/hr$) from 1970 to 2000 extrapolated using the flux estimates listed in Table 1. The line identifies the "no change" tone in the map to help identify increases and decreases in emission relative to that. See color version of this figure in the HTML.

have very different responses to climate warming depending upon changes in subsurface permafrost dynamics that affect the surface hydrology [*Bubier et al.*, 1999; *Bubier et al.*, 1995].

[15] The general implications of the findings presented here are that climate change driven changes in vegetation distribution may be indicators of significant and rapid change in ecosystem greenhouse gas exchanges let alone the obvious direct climatic influence on the rates of ecosystem carbon turnover. This may well help to explain the tight coupling between variations in atmospheric CH_4 concentrations and temperature variations as shown by ice core records [*Petit et al.*, 1999]. Temperature works both directly on CH_4 emissions and indirectly as shown through the physical impacts on the permafrost regime and the associated changes in hydrology and vegetation.

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