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Artificial drainage and associated carbon fluxes (CO_2/CH_4) in a tundra ecosystem

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Abstract

Ecosystem flux measurements using the eddy covariance (EC) technique were undertaken in 4 subsequent years during summer for a total of 562 days in an arctic wet tundra ecosystem, located near Cherskii, Far-Eastern Federal District, Russia. Methane (CH_4) emissions were measured using permanent chambers. The experimental field is characterized by late thawing of permafrost soils in June and periodic spring floods. A stagnant water table below the grass canopy is fed by melting of the active layer of permafrost and by flood water. Following 3 years of EC measurements, the site was drained by building a 3 m wide drainage channel surrounding the EC tower to examine possible future effects of global change on the tundra tussock ecosystem. Cumulative summertime net carbon fluxes before experimental alteration were estimated to be about $+15\,g\,C\,m^{-2}$ (i.e. an ecosystem C loss) and $+8\,g\,C\,m^{-2}$ after draining the study site. When taking CH_4 as another important greenhouse gas into account and considering the global warming potential (GWP) of CH_4 vs. CO_2, the ecosystem had a positive GWP during all summers. However CH_4 emissions after drainage decreased significantly and therefore the carbon related greenhouse gas flux was much smaller than beforehand (475 ± 253 g C-CO_2-e m^{-2} before drainage in 2003 vs. 23 ± 26 g C-CO_2-e m^{-2} after drainage in 2005).

Keywords: carbon balance, energy balance, evapotranspiration, methane, soil water content, tundra

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Introduction

General circulation models predict a stronger increase in temperature and precipitation in higher latitudes than in the temperate or tropical regions (IPCC, 2001, 2007; ACIA, 2004), suggesting that climatic change may affect ecosystems of the far north disproportionally (Maxwell, 1992; Oechel *et al.*, 1993). Arctic ecosystems tend to respond strongly and rapidly to changes in temperature via, for example, species range shifts and the rate and magnitude of biogeochemical cycling (Zimov *et al.*, 1993, 2006a; Oechel & Vourlitis, 1994; Zhuang *et al.*, 2006), highlighting the need for experiments that mimic global change scenarios. Studying the carbon balance of the northern permafrost ecosystems is critical given that they contain 50% of the global belowground carbon stocks, calculated to a depth of 3 m (Jobbagy & Jackson, 2000; Ping *et al.*, 2008; Schuur *et al.*, 2008). A mobilization of these carbon pools by increased temperature will possibly further increase the CO_2 concentration in the atmosphere.

Northern latitudes are also characterized by high methane (CH_4) emission given the large expanse of wetlands and moist tundra ecosystems in which CH_4 is produced in aerobic soils. The efflux from the northern wetlands contributes about 6–8% to global CH_4 emissions (Steele *et al.*, 1987; Whalen & Reeburgh, 1992; Strack *et al.*, 2004). The greenhouse warming potential (GWP) of CH_4 is 23 times that of CO_2 when calculated over an 100-year time horizon (IPCC, 1997, 2007), and ecosystems that act as net carbon dioxide sinks can turn into greenhouse gas sources if CH_4 emissions are high (Corradi *et al.*, 2005).

The GWP of Arctic ecosystems is difficult to predict and existing studies demonstrate contrasting results on the seasonality and variability of GWP attributable to CO_2 and C (Chapin *et al.*, 2000a; Eugster *et al.*, 2000a; Zamolodchikov *et al.*, 2003; Corradi *et al.*, 2005). This uncertainty arises from the multiple biogeochemical consequences that may result from physical changes (e.g. Fig. 1) to terrestrial ecosystems in northern latitudes (McGuire *et al.*, 2002). Changes in precipitation pattern can result in higher soil moisture, which provokes higher CH_4 ef ux (Whalen *et al.*, 1990; Topp & Pattey, 1997). Warming can have a stimulating effect on both, CO_2 and CH_4 production (Lloyd & Taylor, 1994; Updegraff *et al.*, 2001; Grant *et al.*, 2003) and can result in a thawing of permafrost and an increase in active layer depth, making available to oxidative or methanotrophic processes a globally signi cant pool of soil carbon that accumulated during the Pleistocene (Dutta *et al.*, 2006; Zimov *et al.*, 2006a, b). Permafrost melting will also alter soil hydrology by changing the spatial and temporal patterns of water availability which, depending on the local hydrology and deep drainage may either increase or decrease the water table depth. The latter scenario may result in decreased soil moisture during summer. Dry soil conditions imply less CH_4 emissions and a potential stimulation of photosynthesis (Shaver *et al.*, 1992), which may have nutrient fertilizing effects if increased mineralization results (Maxwell, 1992; Oechel & Billings, 1992). If these changes result in an enhancement of ecosystem respiration (ER) that exceeds gross primary production (Fp), ecosystems will act as source of atmospheric CO_2 (Zimov *et al.*, 1993; Oechel & Vourlitis, 1994) and consume small amounts of CH_4. Potential net impacts on both CO_2 and CH_4 across even a partial range of scenarios remain unclear.

Our objective is to investigate the consequences of a global change scenario, namely altered hydrology via a decreased water table, on the greenhouse gas balance of CO_2 and CH_4 of an arctic ecosystem. The hydrology of a tundra ecosystem was altered by introducing a drainage channel. Net ecosystem CO_2 ux (NEE), evapotranspiration (ET) and net CH_4 uxes were observed using a combination of eddy covariance (EC) and chamber measurements before and after the interference. An area in Far-Eastern Federal District of Russia was chosen, since wetlands, often in the form of tundra tussock ecosystems, are common in the region, and the impacts of global change on the function of these ecosystems are poorly understood.

We investigate in particular a likely consequence of active layer depth enhancement via permafrost melting, namely rapid drainage, on subsurface hydrology which has already been observed in the region (S. P. Davidov, personal communication), and the consequences for biosphere–atmosphere exchange (Fig. 1). Northern Siberia is characterized by loamy sediments which are penetrated with a polygonal net of ice wedges with an average width of 3 m and an average polygon size of 10 m in Pleistocene sediments. In contrast the typical

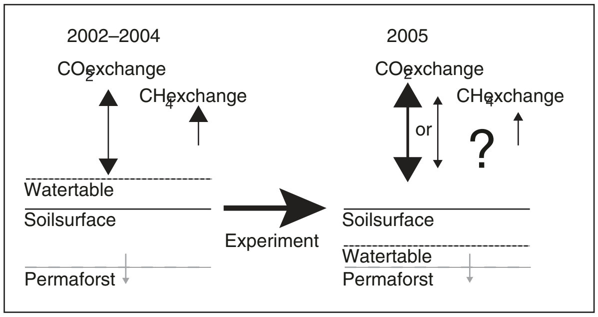

Fig. 1 Scheme of the experiment, showing the planned impact of the drainage channel. Arrows represent the direction and magnitude of CO_2 and CH_4 uxes. The grey dashed indicates the upper part of permafrost. Therefore the difference between soil surface and permafrost represents active layer depth and the grey arrows the change of active layer depth with the progress of the season.

polygon size of Holocene sediments is about 20 m and average width of ice wedges is 1 m (Sachs *et al.*, 2008; Wille *et al.*, 2008). Climate warming is likely to enhance the depth of the active layer and, therefore, leads to melting of the top parts of ice wedges and formation of soil depressions. As a result of the process, hillocks several meters high have begun to appear above the Pleistocene sediment. Finally a network of hillocks and depressions will develop and the maximum outcome has been observed to be the destruction of the present vegetation and typical soils. The minimum observed outcome is the appearance of a net of small channels (2–3 m width), which can already be seen at several places in the region (Zimov *et al.*, 2006b). In either case the hydrological regime is changed severely, having direct in uence on the carbon accumulated during the Pleistocene. The time scales of these processes remain vague because predictions depend on emission scenarios and on the strength of feedback mechanisms. Most scenarios foresee a time scale of about 100 years for widespread changes (Zimov *et al.*, 2006a, b); and we emphasize that limited examples on a shorter time scale have already been observed near the study site.

Material and methods

Study site

The site is located south of the small town of Cherskii in Sakha (Yakutia) Republic, Far – Eastern Federal District of Russia (69°36′47″N, 161°20′29″E). The wetland is part of a wide and at oodplain of the lower Kolyma River, mainly characterized by permafrost soils, which begin to thaw towards the middle of June. Vegetation consists largely of vascular plants, particularly *Carex* *appendiculata* (sedge) forming the tussocks (T) with *Potentilla palustris* (marsh cinquefoil) and the aerenchymateous *Eriophorum angustifolium* (cotton grass) common in the intertussock (IT) space. Other species include *Calamagrostis* sp. (reed grass) and *Carex chordorrhiza* (sedge). Some dwarf shrubs grow on the rather large tussocks, namely *Betula nana* subsp. *exilis* (arctic dwarf birch), *Salix* sp. (willow) and *Chamaedaphne calyculata* (leather leaf). No mosses were found with the exception of a few *Sphagnum* sp. mats. In Cherskii the arctic winter lasts 8–9 months; spring and autumn are rather short (approximately 2–3 weeks apiece). The growing season is not longer than 3 months.

Experimental design

Since the experiment aimed to change the hydrology of the system, a 3 m wide drainage channel (sloped from the experimental site to a river, 1 km distant – Fig. 2a), surrounding the measurement tower at a diameter of 200 m was created by bulldozer in late summer 2004 (Fig. 2a and b). According to Corradi *et al.* (2005), the footprint of the EC measurements rarely exceeded 400 m, and the peak of the source-weight function (Schuepp *et al.*, 1990) almost always resided within a 200 m radius (88% within the distance of 200 m and 6% within 200 and 400 m). Annual climate and mean air temperature during 2003 were most similar to climate conditions following the experimental manipulation in 2005 (Fig. 3a and b). Therefore, 2003 is subsequently used as a baseline for comparison with the experimental treatment in 2005. It should be noted that cumulative precipitation varied highly within both years during July and August, but these differences were restricted to few intensive rainfall events (i.e. 44.8 mm in early August 2005). Snowfall in 2005 (average cover: 50.8 cm) was 1/3 higher than in 2003 (average cover: 38.5 cm) and therefore more water was available from snowmelt, but the undisturbed water tables were equal in July 2003 and 2005 (Fig. 3c) during the peak of the growing season. Differences among the baseline and experimental year in both, precipitation and water table depth observed in August are considered when interpreting results.

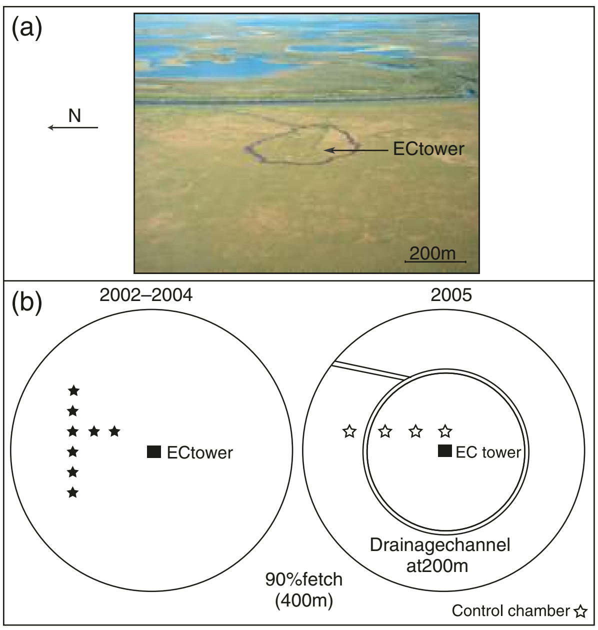

Fig. 2 (a) Photograph of the experimental site from the air in 2005. The drainage channel can be seen as the blue circle with the eddy-covariance tower (EC) in the center. The drainage channel had an average diameter of 200 m. Prevailing wind directions were South-East and North. Photo credit: S. A. Zimov (b) Scheme of the 90% fetch (400 m) of the EC tower for 2003 and including the drainage channel in 2005. Stars show the approximate position of the CH_4 chambers, where black stars represent small chambers and white stars the large chambers including the control chamber (lower right corner).

Carbon dioxide flux measurements

CO_2, H_2O, sensible heat, latent heat and momentum ux measurements were carried out using the EC technique (Baldocchi & Meyers, 1998; Aubinet *et al.*, 2000). Measurements were started on the 16th of May in 2003 and 16th of July in 2005 and lasted until 31st of October in both years. Delays with customs processing altered the start of measurements in 2005. All together, data were collected for 167 days in 2003 (Corradi *et al.*, 2005) and for 104 days during summer 2005. Maintenance and power tests were performed at least once per week. EC measurements were based on a fast response closed path CO_2/H_2O infrared gas analyzer during 2002–2004 (LI-6262, LiCor Inc., Lincoln, NE, USA), an open path CO_2/H_2O infrared gas analyzer in 2004 and 2005 (LI-7500, LiCor Inc.) and a sonic anemometer (Gill Solent R3, Gill Instruments, Lymington, UK) installed at a height of 5.3 m at all times.

Data from the sonic anemometer and the gas analyzer were collected at a rate of 20 (2002–2004) and 10 Hz (2005), respectively, and stored as raw data in a CR5000 Data Logger (Campbell Scienti c, Logan, UT, USA) located at the bottom of a tower in a weather-proof storage box. Due to severe power supply problems during previous years, the main power supply was provided by 80 Ah car batteries, which were charged every 3–5 days. To avoid any damage to the equipment by power uctuations a DC/DC converter was installed to provide constant 12 V.

Meteorological variables including air humidity, air temperature (HMP35D, Vaisala, Helsinki, Finland), air

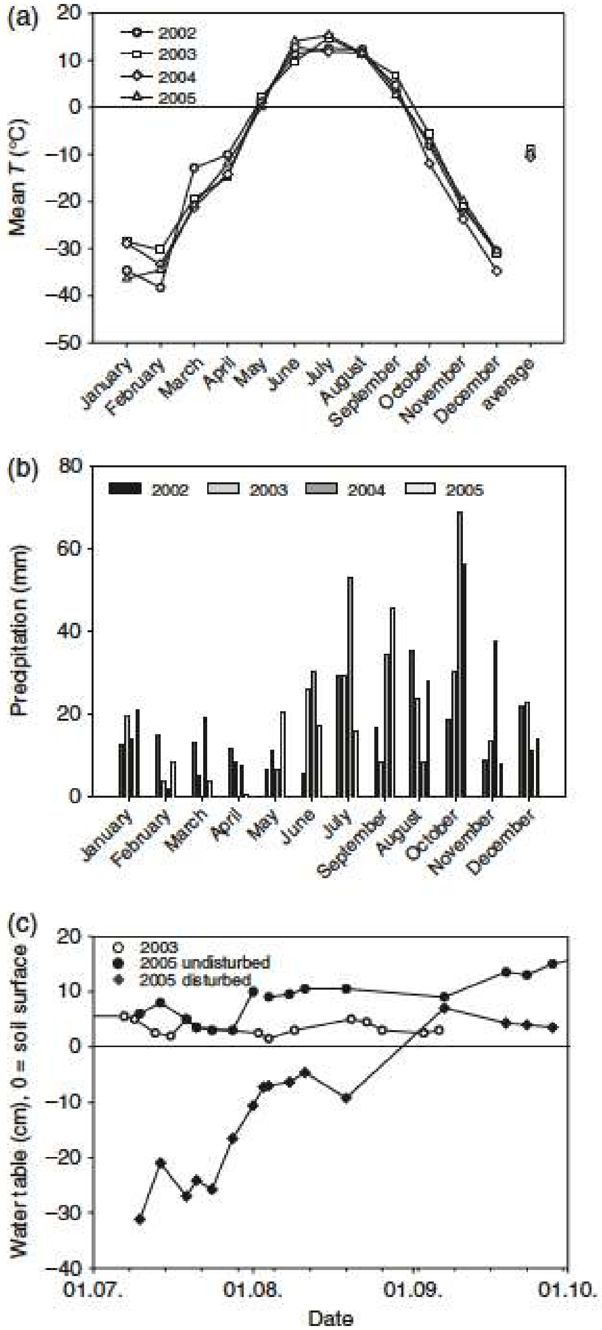

Fig. 3 (a) Mean annual and monthly air temperature (T) for the 2002–2005 measurement. (b) Mean monthly precipitation in mm for the years 2002–2005. (c) Circular dots showing water table in 2003 (white circles) and 2005 before (black circles) and after (black squares) experimental water table manipulation.

pressure (RPT410V, Druck Ltd., Leicester, UK) and total radiation (shortwave incoming/outgoing, longwave incoming/outgoing; net radiometer CNR1, Kipp and Zonen, Delft, the Netherlands) were measured. Summer precipitation was collected using a tipping bucket rain gauge (model 52202, Young, Traverse City, MI, USA). All data were stored in an additional data logger as 10 min averages (CR10X plus multiplexer, Campbell Scientific) at the bottom of the tower.

Five soil heat flux plates (Rimco HP3-CN3, McVan Instruments, Mulgrave, Australia) were placed either below the soil surface of the organic layer or into the top of the tussocks. Six soil moisture probes (ML2x, Delta-T devices Ltd., Cambridge, UK) were also installed in the upper soil surface and in the tussocks. Two soil temperature profiles, both consisting of six platinum resistance thermometers (PT 100, Pico Technology, St Neots, UK), were placed into the soil organic layer at depths of 2, 4, 8, 16, 32 and 64 cm.

Data processing

Postprocessing of the flux data was conducted with the custom software package EDDYSOFT (Kolle & Rebmann, 2007). This included spike detection in the raw data, WPL – correction for density fluctuations for the open path gas analyzer (Webb *et al.*, 1980; Leuning, 2007), transformation from physical values and calculation of the half hourly averages of CO_2 and water vapor fluxes.

Thereafter, technical and meteorological quality checks on the data set were performed to receive a high quality data set. Technical quality checks included the identification of physical (power failure) data gaps, the detection of spikes in the raw data and in the half hour averages as explained by Papale *et al.* (2006) and a rejection of data with high variances in CO_2 and H_2O concentrations, vertical wind velocity (w) and temperature in the raw data (Knohl *et al.*, 2003). Data received by the open path gas analyzer, contained numerous spikes and therefore substantial amounts of data had to be rejected (Table 1). Stationary tests and integral turbulence characteristics were applied on the measured fluxes according to Foken & Wichura (1996). The remaining data set was filtered for low and high friction velocity (u^*), where the EC measurements tend to underestimate/overestimate ecosystem fluxes (Goulden *et al.*, 1996; Zamolodchikov *et al.*, 2003; Papale *et al.*, 2006). Lower and upper u^* thresholds were determined by plotting u^* classes against the 30 min intervals of net ecosystem flux for both years (lower limit: 0.1 m s^{-1} in 2003, 0.15 m s^{-1} in 2005, upper limit: 0.55 m s^{-1} for both years) and the averaged flux of each u^* class (Fig. 4). CO_2 fluxes occurring outside these u^* ranges were rejected. Horizontal advection was not assumed due to the flat terrain with uniform vegetation cover. The ratio of remaining high quality data related to the originally measured is shown for both years in Table 1. Gaps that resulted from instrumental or power failure, from failing the technical and meteorological

Table 1 The magnitude and percentage of half-hourly eddy covariance data remaining after applying quality control checks for 2003 and 2005

	Values	(%)	Values	(%)	(%)
	Single test		Including redundancy		Remaining
2003					
Total number of dataset (measuring period)	8016	100.0			
Physical and technical	1688	21.0	1688	21.0	78.9
Stationarity variable CO_2	2082	25.9	639	7.9	70.9
Stationarity all	2327	29.0	6	0.1	70.9
u^* filtering	3482	43.4	422	5.2	**65.6**
2005					
Total number of dataset (measuring period)	5102	100.0			
Physical and technicals	3017	59.1	3017	59.1	40.8
Stationarity variable CO_2	614	12.0	281	5.5	35.3
Stationarity all	849	16.6	235	4.6	30.7
u^* filtering	3244	63.5	387	7.5	**23.1**

Reasons for the small amount of high quality data are explained in the text.

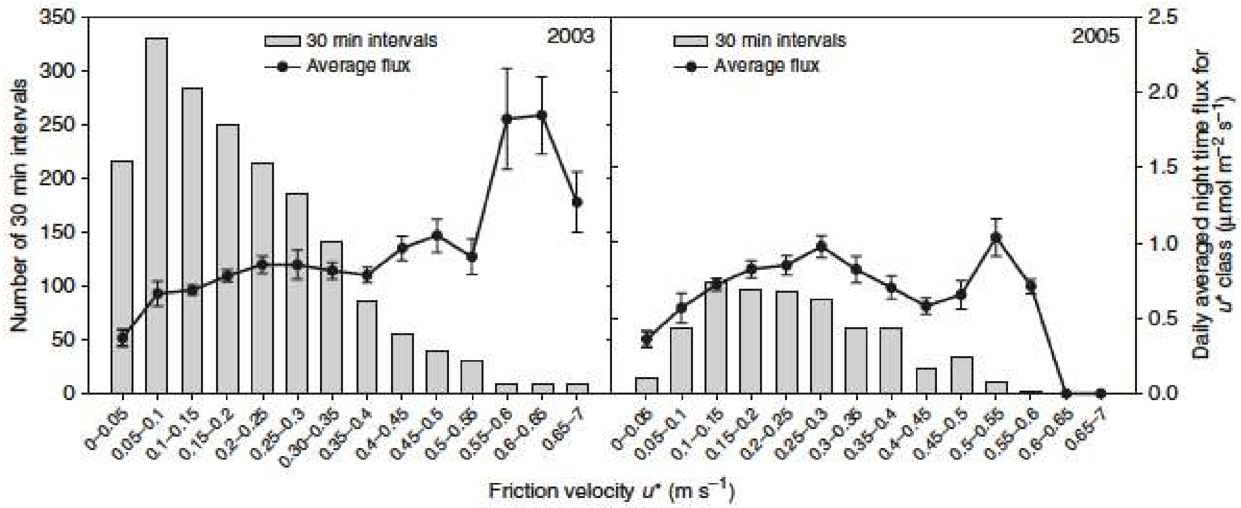

Fig. 4 Daily averaged night time ecosystem exchange (ER) and the amount of 30 min data is plotted against classes of friction velocity (u^*). Bars show the amount of 30 min data and the solid line with black dots the daily averaged net ecosystem exchange for the available amounts of 30 min data and the particular u^* class, ± standard deviation (SD).

quality checks, including u^*- filtering, were filled with several methods:

(1) Gaps which were shorter than 2 h were interpolated by an Akima spline (an interpolation method which is stable to oultiers).
(2) Gaps larger than 2 h were filled by a semiempirical model [ER was calculated with an exponential function, gross primary production was modelled by a hyperbolic response function using global radiation (R_g) as the main driving factor].
(3) Gap-filling was performed using a marginal distribution sampling (MDS) procedure according to Reichstein *et al.* (2005).

The storage term which was calculated by the change of concentration of CO_2 at the top of the tower at 5.3 m within a time span of 30 min had minimal influence on the carbon dioxide fluxes (changes were smaller than 1%) and was therefore not used to correct the turbulent fluxes (Merbold, 2006).

CH_4 flux measurements

CH_4 ux measurements consisted of eight opaque small chambers in 2003/2004 and ve large chambers in 2005 due to the unavailability of the smaller chambers (Fig. 2b). The small chambers were circular plastic constructs ($0.3\,m \times 0.3\,m \times 0.4\,m$), divided into a bottom part, which was inserted 2–4 cm into the top layer of the soil, and a plastic lid with a syringe connector on top, for total closure during the measurements (Corradi *et al.*, 2005). The large chambers ($2\,m \times 2\,m$, 50–60 cm height) were comprised of a wooden frame enclosed on all sides by bitumen paper that provided resistance against all weather conditions, likewise inserted approximately 2–4 cm into the soil and enclosed by a dark polyethylene cover. Inside the chamber a network of tubes was used to obtain a mixed sample from different parts of the chamber. Mixing of air within the small chambers was achieved by using the sampling syringe given the small chamber volume. Air in the large chambers was assumed to be well-mixed, due to differential heating of the polyethylene surfaces, and gas samples were obtained from all areas of the chamber using the tubing network in the enclosed air space. Two gas samples per chamber were taken a least once per week. Chambers for CH_4 measurements were installed on a moisture transect, within the 90% fetch of the tower (Fig. 2b).

CH_4 uxes were determined in all cases by measuring the concentration change inside the chamber. After closing the chamber, samples were taken every 2 min for 8 min. Thereafter, the chamber was opened again to avoid any warming effect (Le Mer & Roger, 2001). Sampling tools were $30\,cm^3$ plastic syringes with a special connector on the front. Before each measurement, 360 mL of air were removed using the syringe to purge the tubing system. Samples were always analyzed within a maximum time of 4 h after sampling on a Shimadzu gas chromatograph (C-R501, Analytical Instrument Recycle, Kyoto, Japan), provided with a ame ionization detector and using nitrogen as carrier gas and outside air (CH_4 concentration 1.8 ppm) as reference. The concentration change inside the chamber is the result of several processes: CH_4 ux through vascular plants, diffusion through soil and water, additional random bubbling and CH_4 consumption by methanotrophic bacteria (Visvanathan *et al.*, 1999; Le Mer & Roger, 2001; Christensen *et al.*, 2003).

During 2002–2004, the eight small chambers were set up on a 100 m transect along the tower (Fig. 2b). In 2005, four big chambers were installed on a moisture transect at different distances from the drainage channel to the tower. Chambers close to the channel represented dry conditions, further distances represented semidry conditions. A control chamber was installed approximately 200 m outside the drainage area to measure similar water saturation as in the previous years (Fig. 2b). Wooden boards were used to avoid physical disturbance of the study plots during sampling.

Modelling

Since temperature is generally found to be the most important factor for short-term variations of ER (Lloyd & Taylor, 1994; Fang & Moncrieff, 2005; van Dijk *et al.*, 2005) an exponential function was tted (Fig. 5a) to model each year's ER:

$$\mathrm{ER} = e^{m(T-T_0)}, \tag{1}$$

where ER is the ecosystem respiration in $\mu mol\,m^{-2}\,s^{-1}$, T is the air temperature in °C, m and T_0 are coef cients. Daily averaged high quality night time data ($R_g < 10\,W\,m^{-2}$) were tted against air temperature to estimate m and T_0 (Fig. 5a) for each summer season (Table 2).

ER was calculated for daytimes by Eqn (1) and used to calculate gross primary production (Fp) by means of the general Eqn (2) for net carbon dioxide ux partitioning.

$$\mathrm{NEE} = \mathrm{F_p} + \mathrm{ER}. \tag{2}$$

Fig. 5 (a) Temperature response curves of averaged night time ecosystem respiration (ER) for the years 2002–2005. Grey dots indicate the eddy covariance measurements with the closed path gas analyzer (2002–2004), and white dots indicate the open path gas analyzer used in 2004 and 2005. The solid line shows the tted exponential curve for each year. ($n_{2002} = 70$, $P < 0.0001$; $n_{2003} = 95$, $P < 0.0001$; $n_{2004closed} = 44$, $P < 0.0001$; $n_{2004open} = 51$, $P < 0.0001$; and $n_{2005} = 52$, $P < 0.0001$). (b) Hyperbolic light response curves of canopy photosynthesis (Fp) for the month July in 2002 till 2005 (grey dots indicate the closed path gas analyzer, whereas white dots indicate the open path gas analyzer). The black curve represents the tted function and the 95% prediction bands for each year (grey). Coef cients are shown in Table 2. (c) Residuals of the hyperbolic curve t for the month July in 2002–2005. (d) Hyperbolic light response curves of Fp for the month August in 2002 till 2005 (black dots indicate the closed path gas analyzer, whereas white dots indicate the open path gas analyzer). The black curve represents the tted function and the 95% prediction bands for each year (grey). Coef cients are shown in Table 2. (e) Residuals of the hyperbolic curve t for the month August in 2002–2005. (f) Response of light saturated Fp to atmospheric vapor pressure de cit (VPD) during July 2002–2005. Dots show the 30 min ux averages.

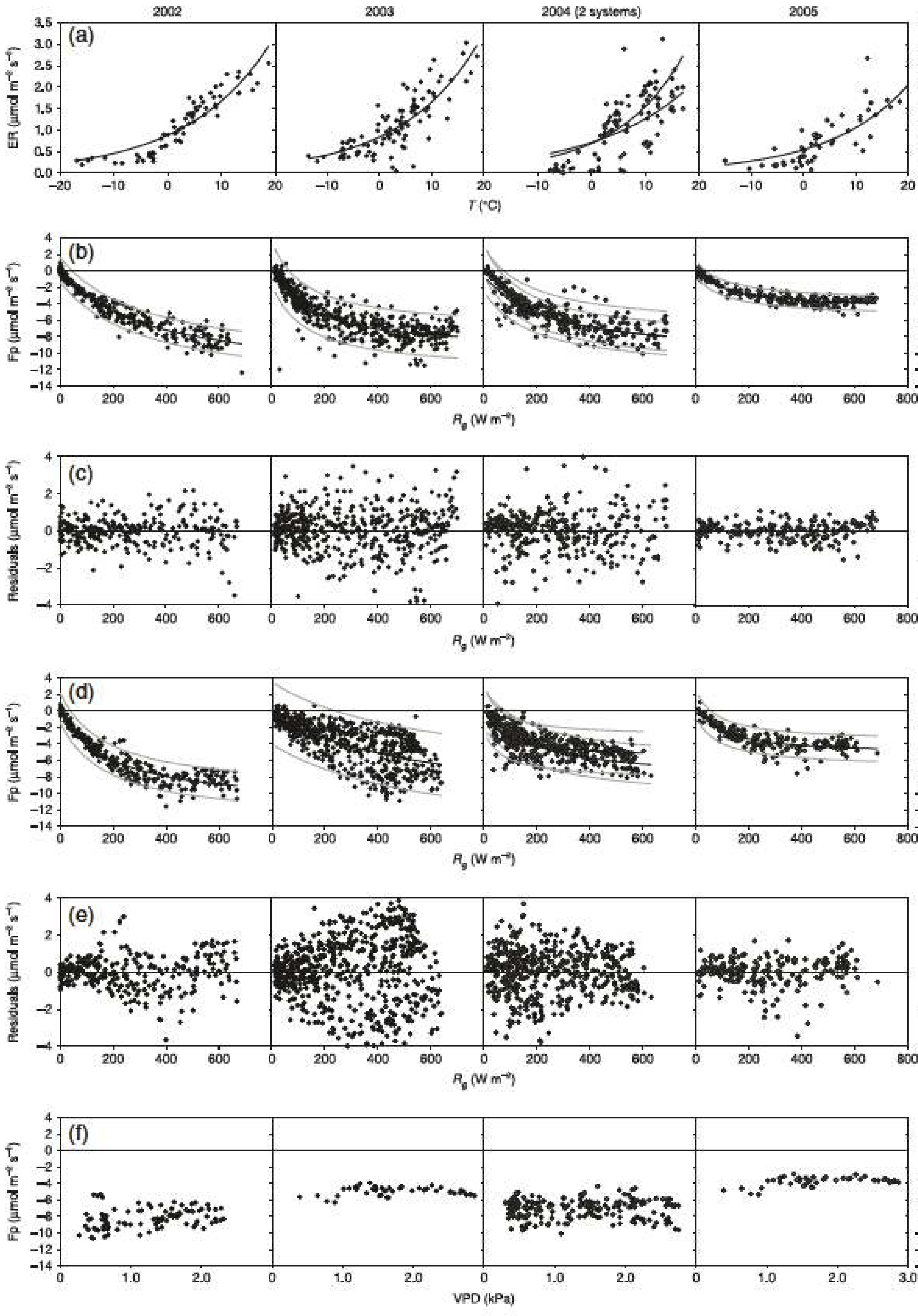
2002
2003
2004 (2 systems)
2005
(a)
ER (μmol m⁻² s⁻¹)
T (°C)
(b)
Fp (μmol m⁻² s⁻¹)
Rg (W m⁻²)
(c)
Residuals (μmol m⁻² s⁻¹)
Rg (W m⁻²)
(d)
Fp (μmol m⁻² s⁻¹)
Rg (W m⁻²)
(e)
Residuals (μmol m⁻² s⁻¹)
Rg (W m⁻²)
(f)
Fp (μmol m⁻² s⁻¹)
VPD (kPa)

Table 2 Parameters for ecosystem respiration (ER) and gross primary productivity (GPP) for July and August periods from 2002 till 2005 as determined from eddy covariance measurements in a tussock tundra ecosystem near Cherskii, Russia

		ER			GPP			
Year	Month	m	T_0	r^2	a	b	c	r^2
2002	July	0.06	1.98	0.82	13.20	321.07	−13.07	0.94
	August	0.06	1.98	0.82	11.98	172.85	−11.57	0.91
2003	July	0.06	2.52	0.61	10.56	131.35	−9.68	0.76
	August	0.06	2.52	0.61	11.88	582.17	−12.17	0.44
2004								
Closed path	July	0.08	4.54	0.61	11.49	160.60	−10.12	0.83
Open path		0.05	5.90	0.42	9.85	180.97	−9.60	0.69
Closed path	August	0.08	4.54	0.61	8.86	194.23	−8.61	0.66
Open path		0.05	5.90	0.42	6.12	63.39	−5.68	0.37
2005	July	0.06	9.15	0.60	4.98	111.46	−4.64	0.85
	August	0.06	9.15	0.60	6.20	85.48	−5.27	0.69

Coef cients a, b and c were derived by tting measured data to R_g.

Gross primary production was then described using a hyperbolic response function

$$F_p = c + \frac{(a \times b)}{(b + R_g)}, \qquad (3)$$

where R_g represents global radiation ($W\,m^{-2}$). Coef cients a, b and c were determined by tting measured data for 4-week periods to R_g using SIGMAPLOT 10 (Systat Software Inc., Chicago, IL, USA) (Table 2). These coef cients vary on the time of season and magnitude of CO_2- ux. Residual plots are added to the gures to visualize model performance.

Energy balance closure was calculated by:

$$H + LE = R_n - G, \qquad (4)$$

where H is the sensible heat ux, LE the latent heat ux, R_n is net radiation and G the soil heat ux. All values are given in $W\,m^{-2}$.

Cumulative ET was calculated from latent heat ux (LE) measurements and the gap lled values from the MDS procedure.

Supplemental measurements

Site phenology was documented by observation and photographs at least once per week and various growing states (e.g. plant growth, senescence, litter fall, freezing) were recorded. Water table and depth of permafrost were measured every 3–5 days at the tower, at each chamber and two different sites in the eld, where the mark zero represented the soil surface. Missing meteorological data were replaced by data from another tower nearby (approximately 7 km northeast of the tower), noting the strong linear relationship between variables recorded at the nearby meteorological stations (i.e. $r^2 = 0.92$ for air temperature, slope = 0.945, offset = 0.5). Mean annual temperatures and winter precipitation were given by the Cherskii Meteorological Station, situated 18 km north of the tower, likewise experiencing very similar climate conditions (S. P. Davidov, personal communication).

Calculation of greenhouse warming potential

The greenhouse gas balance of the system was calculated taking carbon dioxide uxes as well as CH_4 uxes into account. The CO_2 ux was calculated over the peak growing season (starting 16th of July), using the measured and modelled half-hourly values. CH_4 emissions were averaged over a period of 100 days based on two measurements per week and afterwards multiplied by the greenhouse gas warming potential of CH_4 vs. CO_2-23- given by the IPCC (2001, 2007) for the GWP analysis. Since other trace gases were not considered, the GWP is presented as carbon related greenhouse gas ux (C-GHG ux) in CO_2 equivalents. We choose the unit gC-CO_2-e m^{-2} for 100 days (100 $days^{-1}$) to make the C-GHG ux comparable to other terms of the carbon budget (van der Molen *et al*., 2007).

Results

Climate and site hydrology

Mean annual T was approximately −11 °C during 2003 and 2005. Only slight differences between 2003 and 2005 were found when comparing mean monthly temperatures (Fig. 3a). There was a signi cant (two-sample t-test, $P = 0.02$) higher daily soil temperature uctuation in 2005, after drainage, compared with the reference year 2003. Total annual rainfall varied between 200 mm in 2003 and 237 mm in 2005, but the rainfall pattern was different between the years (Fig. 3b), resulting in similar water tables in July, and slightly lower average water table depth in August 2003 compared with the undisturbed site in 2005 (Fig. 3c).

Soil conditions were strongly in uenced by the drainage channel. Substantial ow through the trenched channel was observed in spring 2005, which further enhanced channel width. Flow decreased to near zero in early summer (mid-June), 2005, after the soil was fully drained and peak permafrost melting was yet to occur. The impact of the experiment on ecosystem hydrology can be best described by the water table depth (Fig. 3c). In 2003 the soil was always water saturated and the water table was stagnant above the soil, while in 2005 the water table in the drained eld dropped to 30 cm below the soil surface during the growing season and rose slowly after a large (44.8 mm) precipitation event in early August, that was followed by a cloudy period with low radiation and weak latent heat uxes (Fig. 6). By mid-September water saturation was observed until freezing at the end of the month.

Net C uptake was observed shortly after T rose above 0 °C, which happens on average in late May. Vegetation development during 2002 and 2003 is described in Corradi *et al*. (2005). General vegetation structure did not change through the measurement period. Cumulative ET (16th of July until the 31st of August) was 63 mm in 2003 and 52 mm in 2005 (Fig. 6). For the same time period cumulative rainfall was 37 mm in 2003 and 61 mm in 2005; therefore the water balance was positive over the growing-season measurement periods. Water losses by ET were 20% higher during peak summer 2003 compared with 2005, when the meteorological circumstances were similar, but less water was available (Fig. 6). Evaporative water losses, found during the drainage experiment, can possibly be explained by the amounts of water available due to the melting of permafrost. Roughly 3 cm deeper thawing was found in 2005 compared with 2003.

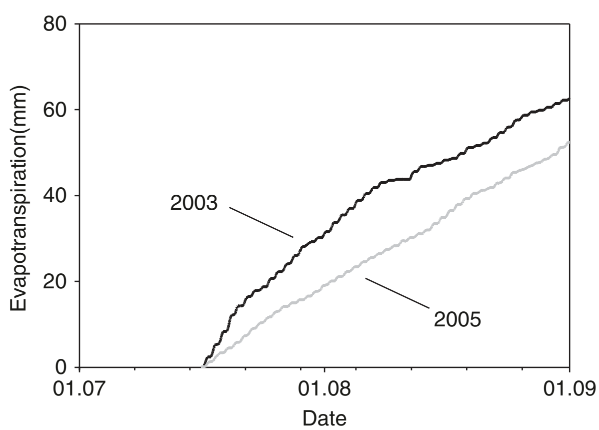

Fig. 6 Cumulative evapotranspiration in mm from 16th of July till 31st of August for 2003 and 2005. Missing values were gap lled using the MDS procedure (Reichstein *et al.*, 2005). MDS, marginal distribution sampling.

CO_2 fluxes

Net ecosystem uptake during daytime decreased after the drainage experiment. The ux partitioning showed that both gross primary production and ER were affected by the experiment. However, the change was not equal within these two processes, because gross primary production decreased severely (shown for July and August 2002–2005, Fig. 5b and c), whereas ER decreased only slightly (Fig. 5a).

Carbon dioxide uxes varied within and among growing seasons. Highest photosynthetic uptake rates ($12.0\,\mu mol\,m^{-2}\,s^{-1}$) were found in the middle of July 2002–2004, shortly after the beginning of the growing season. In 2005, the highest uptake rates ($7.6\,\mu mol\,m^{-2}\,s^{-1}$) were found in the middle of August.

Differences in Fp among the baseline and experimental year were pronounced (Fig. 7a). Maximum Fp in July 2003 was about $12.0\,\mu mol\,m^{-2}\,s^{-1}$, but only $5.4\,\mu mol\,m^{-2}\,s^{-1}$ in July 2005. Similar results were found for August, when highest uxes in 2003 were 10.9 and $7.6\,\mu mol\,m^{-2}\,s^{-1}$ in 2005. An in uence of vapor pressure de cit (VPD) was only observed during the peak of the growing season in 2005 (Fig. 5d). When VPD exceeded 1.5 kPa, Fp decreased slightly. In uences of temperature on Fp were not found (not shown) even if data within speci c thresholds of VPD and under light saturation were compared. Correlation coef cients between measured and modelled data were 0.70 in 2003 and 0.76 in 2005 (Fig. 7b). Energy budget closures were 67% in 2003 and 65% in 2005, respectively and were comparable between the baseline and experimental growing seasons (Fig. 8).

Peak season carbon dioxide balance

Based on the EC measurements, the ecosystem functioned as a carbon sink in 2002 ($-50\,g\,C\,m^{-2}$), a small source in 2003 ($+15\,g\,C\,m^{-2}$), was carbon neutral in 2004 ($+4/-11\,g\,C\,m^{-2}$) and as a small carbon source in 2005 ($+8\,g\,C\,m^{-2}$) (Table 3) over 100 days during the peak growing season (16th of July – 31st of October) of each year. Early season uxes contributed substantially

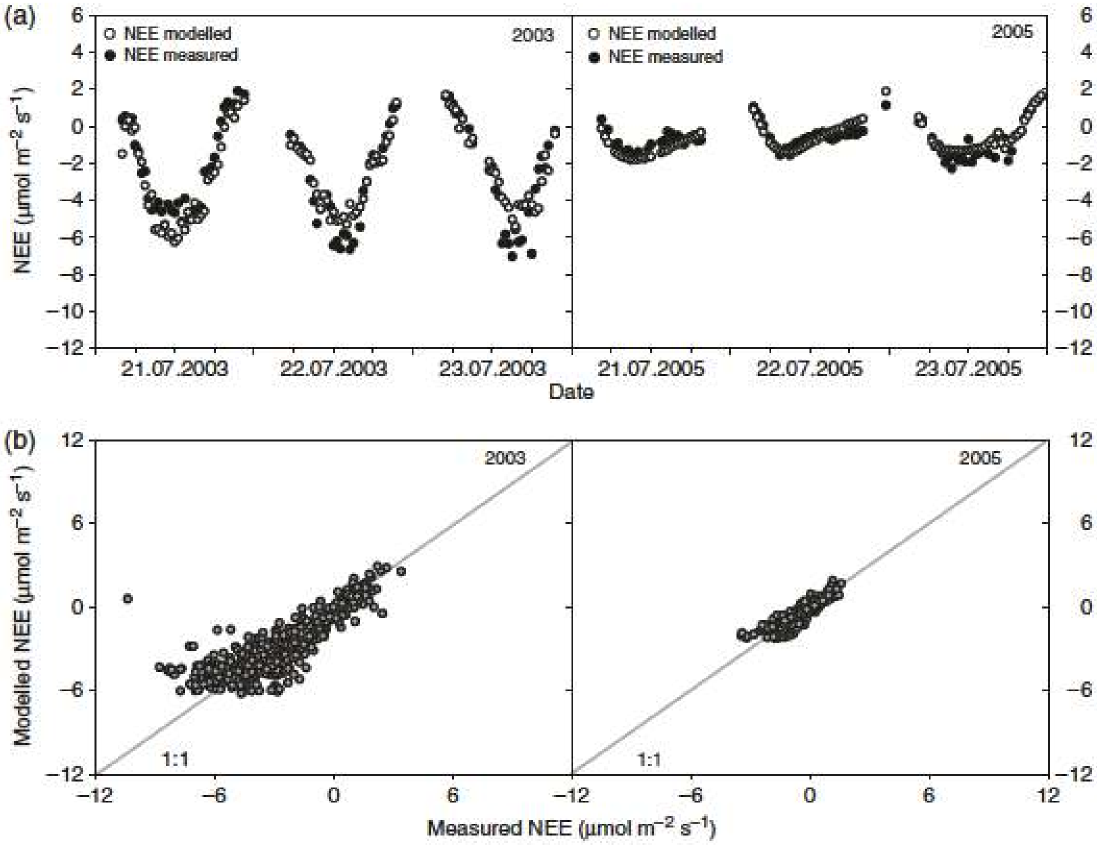

Fig. 7 (a) Modelled and measured net ecosystem exchange for a 3-day period when measurements were available in July 2003 and 2005 during the peak growing season. Black dots represent measurements and white dots represent modelled values. (b) Comparison of modelled and measured net ecosystem exchange for 2003 and 2005. The black line is the regression, whereas the grey line represents the 1:1 line. $n_{2003} = 4503$, $P \bigcirc 0.001$, $n_{2005} = 247$, $P \bigcirc 0.0001$.

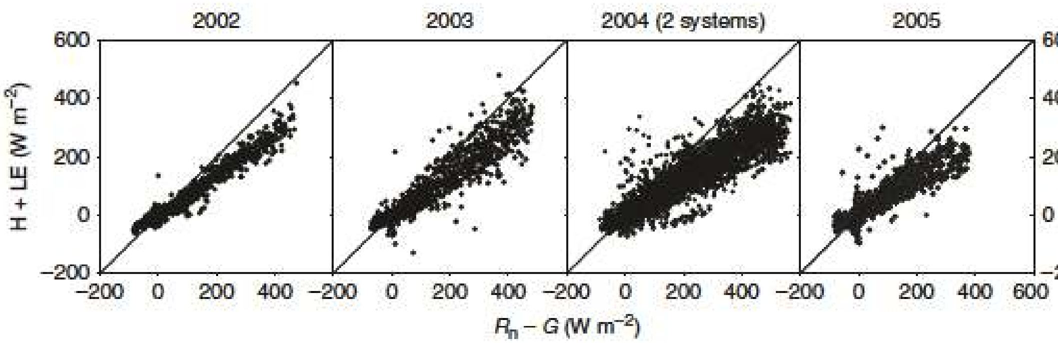

Fig. 8 Energy balance closures for the 2002–2005 measurement periods, shown as in Eqn (4), where H and LE represent the sum of sensible and latent heat flux in W m^{-2}, and R_n-G the difference of net radiation and soil heat flux in W m^{-2}. The grey line represents the 1:1 line. A similar offset was found during all years (2002: $y = 0.68x - 1.02$; 2003: $y = 0.67x + 2.69$; 2004: $y = 0.71x + 15.36$; 2005: $y = 0.65x - 0.25$).

to the total growing season flux (e.g. Heikkinen *et al.*, 2004; Welp *et al.*, 2007) and contributed 50% of the total uptake measured in 2003. Converting these measurements to 2005, the final outcome of the carbon dioxide balances 2003 and 2005 was not changed. The experimental site was a C source in both 2003 and 2005.

CH_4 fluxes

Under water-saturated conditions, the ecosystem emitted substantial amounts of CH_4 (0.065 ± 0.054 mg C_{CH4} m^{-2}s^{-1}). No differences were found between CH_4 efflux rates in 2003 and the rates at the control plot with

Table 3 The budget of the greenhouse gases C-CO_2 and C-CH_4 before (2002–2004) and after (2005) a drainage experiment was conducted in the tundra ecosystem near Cherskii, Russia (16th July – 31st October)

	2002	2003	2004	2005
C-CO_2 (g C m^{-2})	−53	+ 15	+ 4 (closed path) −11 (open path)	+ 8
C-CH_4 (g C m^{-2})	+ 20 ± 15	+ 20 ± 11	+ 24 ± 19	+ 0.6 ± 1.2
C-CO_2 and C-CH‡23 (g C-CO_2e m^{-2})	+ 407 ± 345	+ 475 ± 253	+ 556 ± 437 541 ± 437	+ 22.7 ± 26.4

Carbon dioxide values were modelled as explained in 'Material & Methods' and methane fluxes are given ± standard deviation.

similar moisture conditions in 2005. The cumulative fluxes for the 100-day measurement period were 24 g C_{CH4} m^{-2} during both years. For the drained area in 2005, CH_4 emissions were very low under moist (defined as the moisture range between saturated and dry) conditions (0.0035 mg ± 0.0031 mg C_{CH4} $m^{-2}s^{-1}$) and decreased to almost zero at desiccated patches (0.0002 mg ± 0.001 mg C_{CH4} $m^{-2}s^{-1}$). Cumulative emissions under dry conditions were + 0.64 ± 1.15 g C_{CH4} m^{-2} over the 100 days measured. CH_4 emissions at the undisturbed plots showed a profound seasonal course increasing during early summer, which dropped towards autumn following a possible peak in ecosystem productivity (Fig. 9a).

CH_4 emissions were also influenced by vegetation type. Two chambers (2 and 3), containing similar predominant species [*C. appendiculata* (sedge) and *E. angustifolium* (cotton grass)] showed similar seasonal courses, whereas a third chamber containing primarily *B. exilis* (dwarf birch), *Salix* sp. (willow) and *C. calyculata* (leather leaf) did not display a seasonal course (Fig. 9b), showing instead three peak efflux periods. These peaks did not correlate with soil moisture or air temperature (Fig. 9b).

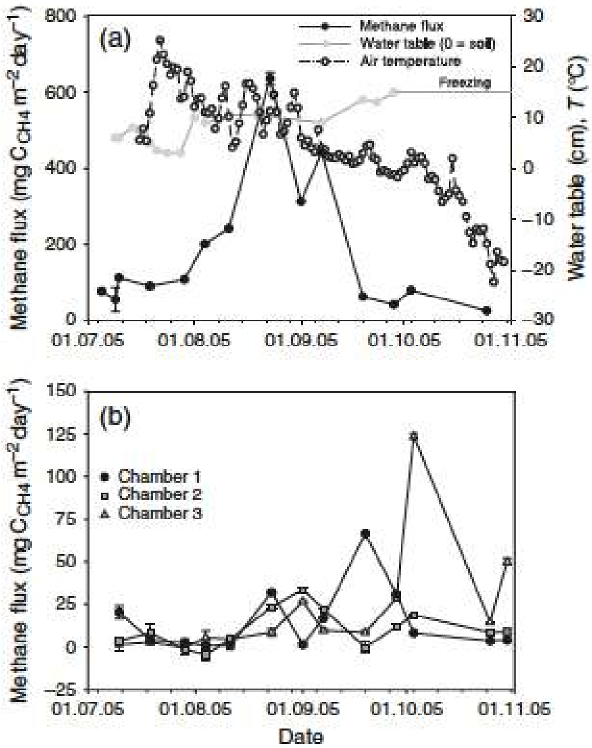

Fig. 9 (a) Seasonal course of methane efflux in 2005 under water saturated conditions. Black dots represent the methane efflux, grey dots represent, the water table in cm above the soil surface (0 = soil surface) and white dots represents daily averaged air temperature. (b) Methane flux from the beginning of July till the beginning of October in different chambers in 2005, while chambers 2 and 3 have the same species (primarily *Eriophorum angustifolium* and little *Carex appendiculata*) composition whereas chamber 1 differed (*Carex appendiculata*, *Carex chordorrhiza*). All values ± standard deviation.

Discussion

This study demonstrates the ecosystem C flux consequences of an experimental drainage of a wet tundra ecosystem. Three years of measurements (Corradi *et al.*, 2005) were followed by an experimental alteration in ecosystem hydrology by building an artificial drainage channel, in order to simulate a potential impact of global warming on tundra hydrology (Figs 1 and 2). The first question to discuss is: how well does the experiment meet probable changes in hydrology with changing climate? Decreases in water table depth as a result of permafrost degradation have been observed in the study region. Modelling and observational studies have provided evidence about ongoing changes in hydrology and vegetation structure in northern ecosystems (Chapin *et al.*, 1995; Walker *et al.*, 1995; Starfield & Chapin, 1996; Hobbie *et al.*, 1999; Kittel *et al.*, 2000; MacDonald *et al.*, 2000; Sturm *et al.*, 2001). Water losses from ET are likely to increase with a change in vegetation in future: for example the increased leaf area index supported by invading shrub vegetation (Eugster *et al.*, 2000a; Chapin *et al.*, 2000b). Changes in arctic ecosystems associated with an increase in soil temperatures and ET have been demonstrated by several studies (e.g. Oechel & Vourlitis, 1994), and multiple symptoms of arctic ecosystem change may result in dryer soil moisture conditions, including enhanced or decreased ET and/or enhanced water loss from the rooting depth following permafrost melting.

For ideal comparison of the carbon fluxes (CO_2 and CH_4) from the wet tundra ecosystem, when changing one crucial variable, soil moisture, it is important to minimize the influence of other variables, e.g. annual variability in temperature, radiation or precipitation (Beringer *et al*., 2005). This can be achieved by measuring ecosystem fluxes several years before the experiment and choosing the year with the most similar weather conditions for comparison with the year of experiment. The year 2003 was selected as baseline because it was closest to the experimental year 2005, even though complete similarity is not possible in a field study. However, for better understanding we provide response curves of ER and Fp from the whole measuring period, a total of four summer seasons (Fig. 5).

CO_2 flux measurements

During the past decade, the EC technique has become a primary method for measuring trace gas exchange between terrestrial ecosystems and the atmosphere given its ability to measure flux noninvasively over large spatial expanses (Wofsy *et al*., 1993; Valentini *et al*., 1996; Baldocchi *et al*., 2001; Rebmann *et al*., 2005). The EC method is most applicable over (1) flat terrain and (2) within homogeneous surrounding vegetation (Baldocchi, 2003). Both of these assumptions are fulfilled at our site (Schuepp *et al*., 1990; Rebmann *et al*., 2004; Foken *et al*., 2005). Still, we are aware of some technical limitations of our study. One may result from differences in our equipment: an open path IRGA was used in 2005, while a closed path IRGA was installed in 2003. In the year 2004, both instruments were installed at the tower and showed similar results for CO_2 fluxes ($r^2 = 0.86$, $y = 1.0023x + 0.53$). Comparison of the two measured ecosystem fluxes were possible due to the number of quality checks applied to the full measurement record (Rebmann *et al*., 2005; Papale *et al*., 2006). Filtering for precise thresholds of friction velocity was used in both years to avoid over- and underestimation of the fluxes due to lack of the mechanical production of turbulent kinetic energy (Eugster & Siegrist, 2000b). Energy balance closures were analyzed to qualify the EC data (Fig. 8), as performed in previous studies (e.g. Falge *et al*., 2005; Barr *et al*., 2006; Yu *et al*., 2006). Numerous global studies demonstrate that surface energy imbalances typically range from 10% to 30% (Foken, 2008). Several errors are associated with the measurement processes (e.g. systematic errors), the different scales or layers influencing the measurements (e.g. footprint) and due to the loss of low and high frequency contributions to the energy transport (Cava *et al*., 2008; Foken, 2008). For wetlands with permafrost layers the imbalance usually is larger since the energy required for the phase transition that occurs during permafrost melting, and for warming of liquid water are pronounced and not included in this calculation (Rouse, 2000).

Measurements demonstrated decreases in canopy photosynthetic capacity as well as in total ER after experimental manipulation. The expected increase in ER under drained soil conditions was not evident over the measurement period. One possible explanation is a lower physiological activity of wetland plants under changed soil water conditions (water stress) noting the strong coupling between photosynthetic uptake and metabolic respiratory losses (Högberg *et al*., 2001). We assume that the decrease in photosynthetic uptake rates we found has resulted in a decrease in root respiration (Joiner *et al*., 1999; Flanagan *et al*., 2002; Grogan & Jonasson, 2005; Moyano *et al*., 2007). Typical peat bog species are neither adapted to high temperatures nor to a significant change in the surrounding water conditions.

A higher model complexity seemed to be inappropriate as shown in other modelling studies on high latitude ecosystems (Williams *et al*., 2006). There might be a small overestimation of seasonal fluxes due to ignoring an influence of VPD on canopy photosynthesis, but over the course of the growing season situations with VPD $>$ 1.5 kPa were rare. In addition, there might also be a decoupling of the system as suggested by McNaughton (1994).

When summing CO_2 data for the different measured years, the balances fluctuated between -50 and $+15\,g\,C\,m^{-2}$ in the years 2002–2004, when the system was undisturbed. The balance did not change in the year after experimental alteration (2005), when the coincidental decrease of Fp and ER resulted in an almost balanced NEE ($+8\,g\,C\,m^{-2}$). This is not significantly different from other years since we assume a conservative uncertainty estimate of $\pm 50\,g\,C\,m^{-2}$ for all balances. Studies in other undisturbed high latitude tundra ecosystems have shown similar carbon exchange values as measured here:, sites were $47\,g\,C\,m^{-2}\,yr^{-1}$ in Alaska in 1994 and 1995 (Vourlitis & Oechel, 1999) and 54–61 $g\,C\,m^{-2}\,yr^{-1}$ in central Siberia in 1998, 1999, 2000 (Arneth *et al*., 2002) compared with an enhanced cumulative uptake (31–180 $g\,C\,m^{-2}\,yr^{-1}$) at lower lattitudes in Canada (Trumbore *et al*., 1999).

CH_4 flux measurements

CH_4 emissions are characteristic of the Arctic ecosystems due to the anaerobic decomposition of organic matter. The residence time of CH_4 is short under aerobic soil conditions, because it is oxidized to carbon dioxide by methanothrophic bacteria (Topp & Pattey, 1997). Therefore a decrease in CH_4 emissions upon drainage is expected.

In this context it is even more remarkable that the amount of respired CO_2 decreased with drainage, because the oxidation of CH_4 to CO_2 may be expected to increase the ecosystem CO_2 efflux. This can be shown by a simple calculation: if CH_4 production is reduced by 50% from estimated 24–12 $g\,C\,m^{-2}$ throughout the growing season but CH_4 efflux is only around 1 $g\,m^{-2}$, about 11 $g\,C\,m^{-2}$ are oxidized and increase CO_2 efflux. A possible explanation can be the transport of C from the site as dissolved organic carbon via the channel.

Various studies (Corradi *et al*., 2005; Zhuang *et al*., 2006; Strack & Waddington, 2007; Mastepanov *et al*., 2008) have already shown that quantifying the CH_4 flux of experimental sites across space and time is highly uncertain, due to micro topography, vegetation structure and hydrology and stochasticity. However, the estimates seem to be rather relevant, when comparing previous measurements (undisturbed) with the control measurements from 2005 ($r^2 = 0.85$). An increase of the CO_2 efflux, due to higher oxidation rates of CH_4 with lower water table and close to plant roots (Frenzel, 2000) was not conclusively demonstrated here.

Total greenhouse gas balance

The drainage experiment had a notable impact on CO_2 and CH_4 fluxes. When considering the GWP budget of these species (IPCC, 2001, 2007), the CH_4 emissions during 100 days (16th July – 31st October) in 2003 comprised C-GHG flux equivalent of 460 g CO_2 and exceeded the net loss of CO_2 (+ 15 $g\,C\,m^{-2}$) by a factor of 30. The result for the observed period in 2003 was a total C-GHG source of approximately 475 ± 253 g C-CO_2-e m^{-2}. In contrast, the emissions during the 100 days in 2005, including CH_4 and CO_2 emissions, were only around 22 ± 26 g C-CO_2-e m^{-2} (Table 3). The GWP impact of the site on radiative forcing in the atmosphere was substantially lower after building the drainage channel. Assuming a conservative error term of $\pm 50\,g\,C\,m^{-2}$ for EC measurements after Baldocchi (2003), does not change our interpretation.

Conclusions

Artificial drainage of a wet tundra ecosystem in the Far-Eastern Federal District, Russia, dramatically decreased CH_4 efflux (24 $g\,C\,m^{-2}$ to $<1\,g\,C\,m^{-2}$) and changed ecosystem-level CO_2 flux only slightly to a smaller source on the growing season time scale (+ 15 to + 8 $g\,C\,m^{-2}$ release). Ecosystem CO_2-fluxes varied between the years before the experiment ($-50\,g\,C\,m^{-2}$ uptake in 2002, + 15 $g\,C\,m^{-2}$ in 2003 and $+4/-11\,g\,C\,m^{-2}$ in 2004).

The results highlight the sensitivity of high-latitude ecosystems to global change scenarios in the short term. Over longer periods, we expect a change in vegetation as proposed by Borken *et al*. (2006), Dhareesank *et al*. (2005), Nieveen *et al*. (2005), and subsequent recovery of both ecosystem photosynthesis and ecosystem respiration (Verville *et al*., 1998; Grogan & Chapin, 2000; Mikan *et al*., 2002) and we will continue to monitor the impacts of drainage on the GWP budget of the ecosystem.

Changes in hydrology as drivers of vegetation dynamics and soil temperature variations have not been considered in climate change scenarios, although they are very important factors for the melting of permafrost (Young *et al*., 1998; Elberling, 2003; Shaver *et al*., 2006). The release of Pleistoscene Carbon, stored in the permafrost, can have a significant impact on future climate (Zimov *et al*., 2006a, b).

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