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Author(s)	DESYATKIN, Alexey R; TAKAKAI, Fumiaki; FEDOROV, Pavel P; DESYATKIN, Roman V
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Effect of Human Activity on Carbon Balance in Meadows in a Thermokarst Depression in Siberia

DESYATKIN Alexey R.[1]*, TAKAKAI Fumiaki[1], FEDOROV Pavel P.[2], DESYATKIN Roman V.[2], and HATANO Ryusuke[1]

[1] Graduate School of Agriculture, Hokkaido University, Kita-9 Nishi-9, Kita-ku, Sapporo, 060-8589, Japan
[2] Institute for Biological Problems of Cryolithozone, Siberian Branch, Russian Academy of Science, Lenin Ave. 41, Yakutsk 677980, Russia

Abstract

There are around 16,000 thermokarst depressions, also known as "Alas", located in Central Yakutia lowland within the boreal forest region with a total area of 440,000 ha. The Alas covers 17% of the total land area of Central Yakutia, Russia. Steppe grasses are widely distributed on these formations replacing boreal forests during the Alas development. Alas soils are formed with the combination of buried and superficial horizons of lake-marsh genesis and with high carbon (C) stock in the stage of thermokarst formation during the early Holocene. During the xeromorphic stage, meadows developed with the fluctuation of Alas lake. We studied the carbon budget in an Alas near Yakutsk, Russia during the snow free period (86 days) in 2006. Soil C storage in 0-40cm top layer amounted to 49.7 Mg C ha^{-1} in the forest surrounding the Alas. On the other hand, the soil C storage in the middle grassland of Alas was 4.3 times larger than in the forest, but the dry grassland reduced soil C storage to 19.1% of the forest. The cumulative microbial respiration (Mg C ha^{-1} $period^{-1}$) was estimated as 1.81 in dry grassland and 1.89 in middle grassland, which were smaller than that in forest (2.86). The net ecosystem production (NEP) and the net biome production (NBP=NEP-harvest) were positive in dry grassland (0.420 and 0.162 Mg C ha^{-1}, respectively), while being negative in middle grassland (-0.581 and -1.21 Mg C ha^{-1}, respectively) indicating that the larger soil C storage area reduced more C. The hay harvest as well as the microbial respiration could be strong factors in reducing C budget of grasslands in thermokarst depression of boreal forest region.

Key words: carbon balance, central Yakutia, grassland, microbial respiration, thermokarst depression

Introduction

Permafrost regions occupy about 25% of the terrestrial surface in the Northern Hemisphere, and more than 60% of it is in Russia (Kudrjavtsev *et al*. 1978; Brown and Grave 1981). Changes in permafrost have important implications for natural ecosystems. The permafrost degradation and human settlement due to thermokarst process may lead to a drastic distortion of terrain and to changes in hydrology and vegetation, and may lead ultimately to transformation of the existing landforms. The fluctuation of thermal conditions during the early Holocene led to thermokarst degradation of ice complex in Central Yakutia (Bosikov 1991). This thermokarst degradation process has four different stages, and finally forms a stable thermokarst depression, which is called "Alas" (Fig. 1). Steppe grasses are widely distributed on these formations replacing the boreal forests during the Alas development (Fig. 2). Around 16,000 Alases are located in Central Yakutia lowland with the total area of 440,000 ha, which is 17% of the total land area of Central Yakutia (Bosikov 1991). The Alas size varies from 0.1 to 15 kilometers in diameter and from 3 to 40 meters in depth of depression. The central Yakutia region is a well-known example of thermokarst terrain (Soloviev 1959; French 1996) as illustrated in Fig. 2.

Alas development has two stages of soil formation: hydromorphous and xeromorphous. During the hydromorphous stage, residue of plankton and benthos are accumulated in the bottom of thermokarst lake, and organic and organic-mineral deposits i.e. sapropels are generated. During the gradual drying of alas lake on the lowest places of thermokarst depression, gleying of soil accompanied by accumulation of a large amount of organic matter in the form of lake deposits and turf are progressing (Desyatkin 1981, 1984) (Fig. 3).

The second (xeromorphous) stage of formation is characterized by an accumulation of phytogenic organic matter in soil structure (Desyatkin 1981, 1984; Matsuura *et al*. 1994). At this stage, sod and humus accumulation in the soil are progressing in the meadow vegetation of dried alas lake area. The Humus-accumulative horizons passed in the recent lake phase development, containing surface humus or peat horizons. The combined lake-soil accumulation of organic matter in soils leads to drastic increase in

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carbon stocks in Alas soils.

The accumulation of organic deposits at the bottom of periodically appearing and disappearing thermokarst depression lakes and formation of peat on lower parts of the depression thus lead to the accumulation of organic material in thermokarst depressions. Fast dynamics of thermokarst depression relief promote redeposition of grounds and occurrence of buried humus, peat, and sapropelic horizons in a soil structure (Gavriliev *et al*. 1983; Bakulina *et al*. 2000). As a result, stocks of C in Alas soils considerably exceed the content of C in boreal forest soils (Matsuura *et al*. 1994). Carbon stocks in Alas soils are 7-10 times larger than that in forest soils (Desyatkin and Desyatkin 2006).

One of the most likely and important feedbacks from sustained warming in high-latitude ecosystems is the thawing of permafrost soils and the release of soil C to the atmosphere by microbial organic matter decomposition as carbon dioxide (CO_2) and methane (CH_4) (Oechel *et al*. 1993; Zimov *et al*. 1993; Goulden *et al*. 1997; Melillo *et al*. 2002), or by leaching out as dissolved organic C (Freeman *et al*. 2004; Frey and Smith 2005). The soil organic matter is among the largest global reservoirs that exchanges C with the atmosphere at time scales ranging from a few years to several hundreds of years (Trumbore *et al*. 1996). It is estimated that nearly one third of the world's total soil organic C inventory of top 1m of soil profile (approximately 455 Pg C, Pg = 10^{15}g) is stored in arctic and boreal regions (Gorham 1991). This pool of soil C, protected by cold and waterlogged conditions, is thought to be highly susceptible to changes in temperature and permafrost thawing. Therefore, a huge C stock in thermokarst grassland in Central Yakutia may become a latent risk of large C emission to the atmosphere in the future global warming scenario.

The main purpose of this work is to evaluate the influence of human activities on C balance in grasslands of thermokarst depression in Central Yakutia.

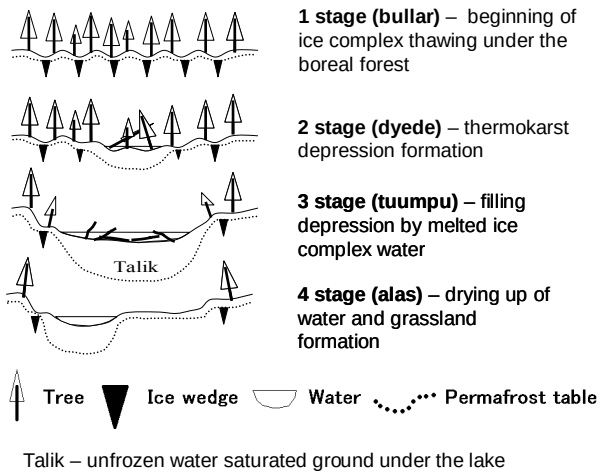

Fig. 1. Schematic diagram of the Alas formation process (After Soloviev 1959).

Fig. 2. Distribution of thermokarst in Central Yakutia.

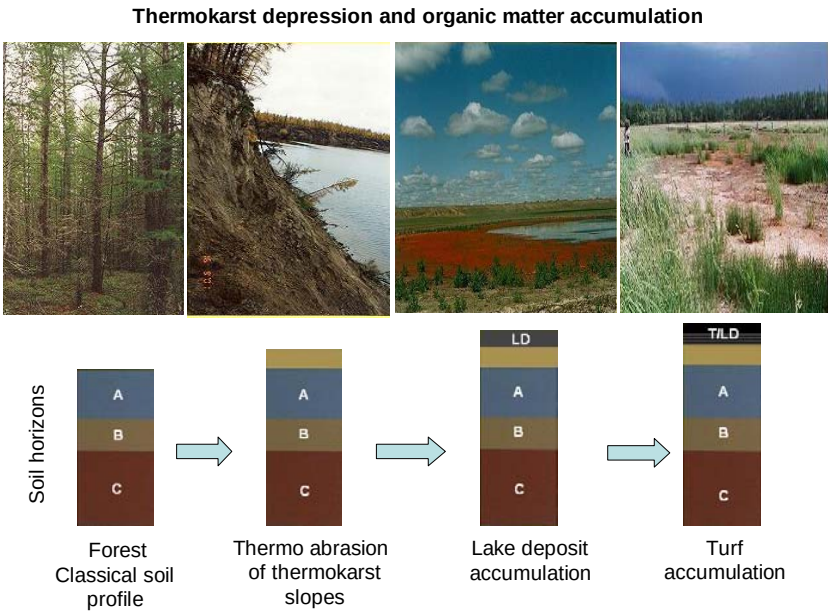

Fig. 3. Soil formation process in thermokarst depression. A, A horizon; B, B horizon; C, C horizon (mother material); LD - lake deposits; T/LD - turf and lake deposits.

Materials and methods

Study Site

An Alas located on the east bank of Lena River, around 50 km to the east from Yakutsk city, was selected for this study. The area of studied Alas (Ulakhan Sukkahan Alas, 62º08'49"N, 130º30'49"E, Fig. 4) is 64 ha, which consists of grassland and a pond in its center (Fig. 4). The grassland in the Alas was divided into two plots (dry and middle grasslands) according to the difference in soil moisture and vegetation type (Fig. 4). To make this scheme we used theodolite from the topographic landmark located at 40 m near the edge of thermokarst depression. It is generally used dividing of thermokarst grassland to the four different belt of vegetation around thermokarst depression lake: vegetation of lake, wet grassland, middle grassland and dry grassland (Fig. 4).

The forest surrounding the Alas is dominated by the *Larix gmelini* and *Vaccinium vitus-idaea*. The dominant vegetation of the dry grassland is *Poa pratensis* and *Elytrigia repens*, of the middle grassland is *Puccinellia tenuiflora* and of the wet grassland is *Carex orthostachys*.

The management of Alas grassland includes grazing and hay harvesting. Cattle grazing take place only in early June and end of September, for around two weeks each time. The season for hay harvesting is the end of July or early August during one week depending on highest above-ground biomass at the time.

The annual mean temperature of this region is -9.9ºC with average temperatures in January and July of -41.2 and 18.7ºC, respectively. The annual mean precipitation during 100 years is 240 mm, 150 mm of which occur as summer precipitations. The actual precipitation of growing season (May-September) for the studied year (2006) amounted to 245mm (Yakutsk weather station data). Thus 2006 can be characterized as an "extremely wet" year. Due to the high precipitation in summer, the area of Alas pond was expanded. The wet grassland plot was flooded by pond water continuously, and middle grassland was also flooded temporarily in September. Therefore, a measurement plot in wet grassland could not be established in 2006. Consequently, a transect across the forest and Alas grasslands (dry and middle grasslands was made, along which all measurements were carried out (Fig. 4).

Soil C content measurement

The study of soil C was also conducted in 2006. The soil C content was measured at 3 sites (forest, dry and middle grasslands) in the Alas. Soil samples were taken from the upper two horizons of soil profile at the same time of root sampling from a depth of 0-40 cm. The air dried samples were passed through a 2 mm sieve and were analysed for C and N contents by dry combustion method using Sumigraph NC-1000 (Sumika Chemical Analysis Service, Osaka, Japan). The soil C storage in the active layer was estimated by using the values of bulk density, horizon thickness, and C content.

Soil and microbial respiration measurement

Soil CO_2 flux (soil respiration) consists of root and microbial respirations. For microbial respiration measurements, bare soil plots were made in forest, dry, and middle grasslands. For this, a soil column of 1 m^2 area and 40 cm depth was made and was protected by a nylon sheet to prevent root penetration inside the column. Roots were completely removed from the bare soil plots. Measurement and estimation of microbial respiration was conducted by the same methods as for soil respiration.

The measurement of soil and microbial respirations were carried out once or twice a month from June to September 2006 by using a closed chamber technique as proposed by Sawamoto *et al.* (2000) and Morishita *et al.* (2003). Six stainless steel chambers, 25 cm in height and 18.5-21.0 cm in diameter with a detachable lid, were used. Each three chamber was set on the forest floor and on the soil surface in different vegetation belts of Alas grasslands (dry and middle). Before the measurement of soil and microbial respirations, green parts of plants on the forest floor and grassland were

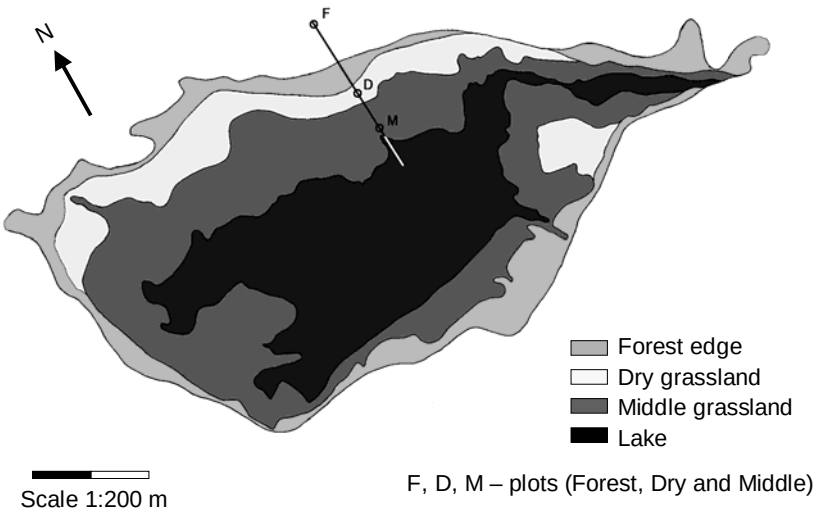

Fig. 4. Spatial structure of studied alas, made by theodolite (July 2006). Studied transect is shown in this figure as a line from forest to lake. Plots: F-forest, D-dry grassland, M-middle grassland.

removed carefully in order to exclude plant respiration. Chambers were then installed at 3 cm depth into the soil and were kept overnight to eliminate the fluctuation due to disturbance. In the following day, a 250 mL gas sample was taken into a Tedlar bag before and after 6 minutes of setting up the chamber lid. At the same time, air temperature inside the chamber was also taken. When the soil surface was flooded by pond water, CO_2 flux from the water surface was measured.

Soil temperature and moisture were measured at each plot. Soil temperature was measured with a digital thermometer at a depth of 5 and 10cm. Soil moisture at the soil surface (0-5 cm) was estimated by a gravimetric method and was indicated as the volumetric water content. All the measurements were taken with three replications.

Gas analysis and calculation of soil and microbial respiration

CO_2 concentrations in air samples taken in Tedlar bags were analyzed by an Infrared Gas Analyzer (ZFP9, Fuji Electric Co., Ltd., Tokyo, Japan).

CO_2 and microbial respiration fluxes were calculated according to the change in gase concentration in the chamber against the closure time:

$$F = \rho \times h \times (\Delta c/\Delta t) \times [273/(273+T)]$$

where F is the CO_2 flux (mg C m^{-2} h^{-1}), ρ is the gas density (CO_2-C = 0.538×10^6 mg m^{-3}), h is the height of the chamber from soil surface (m), $\Delta c/\Delta t$ is the change in gas concentration inside the chamber during the sampling period (m^3 m^{-3} h^{-1}), T is the air temperature inside the chamber (^oC). A positive flux denotes the emission from the soil, whereas a negative flux denotes the uptake from the atmosphere.

The cumulative soil and microbial respirations were calculated from the flux values as follows:

Cumulative soil and microbial respirations = $\sum_{i=1}^{n-1} F_i \times D_i$

where F_i is the mean gas flux (kg C ha^{-1} d^{-1}) between two sampling times (i.e., for time interval i) D_i is the number of days in the sampling interval, and n is the number of sampling times.

Measurement of net primary production (NPP) in grassland

The NPP was estimated using a harvest method. After grass harvesting, we divided the biomass into above and below-ground. The samples of above-ground biomass were taken at three replications of 50x50 cm^2 every month, four times during the growing season in 2006. The below-ground biomass was taken at 3 replications of 50x25 cm^2 with a depth of 40 cm three times during the growing season. The NPP is defined as the total new organic matter produced during a specified interval (Clark *et al*. 2001). The local farmers were interviewed for getting information on harvest of hay.

C balance calculation

Net ecosystem production (NEP) and net biome production (NBP) were calculated as follows:

NEP = NPP – microbial respiration;

NBP = NEP – yield.

The positive values of NEP and NBP indicated the net C loss from the ecosystem.

Results

Soil C in forest and Alas soils

The soil C storage in 0-40cm topsoil in the forest amounted to 49.7 Mg C ha^{-1}. On the other hand, the amount was 9.5 Mg C ha^{-1} in dry grassland, which was only 19.1% of the C storage in the forest soil. On the other hand, the soil C storage in the middle grassland was 214 Mg C ha^{-1}, which was 4.3 times larger than that in the forest soil (Table 1).

Soil and microbial respiration from forest and Alas grassland

In 2006, precipitation during the plant growing season (May–September) was abnormally high (245 mm, Yakutsk weather station data), and soil respiration did not show any clear seasonal change depending on soil temperature, which usually increases during the summer and decreases in the autumn. The maximum

Table 1. Soil carbon storage in the studied Alas (Ulakhan Sukkhan Alas) in upper 40 cm.

Plot	Horizon	Thickness (cm)	Bulk density (Mg m^{-3})	C content (%)	C storage (Mg C ha^{-1})
Forest	O	3 cm	0.06	28.3	14.6
	A	6 cm	0.40	9.1	30.5
	B	31 cm	1.0	1.2	4.6
	Total				49.7
Dry grassland	A	5 cm	0.90	3.51	5.6
	B	35 cm	1.2	0.96	3.9
	Total				9.5
Middle grassland	A	25 cm	0.80	9.73	194
	B	15 cm	1.3	3.21	20.1
	Total				214

soil respiration in forests (237 mg C m^{-2} hr^{-1}) and dry grasslands (236 mg C m^{-2} hr^{-1}) was observed in June, following a decreasing trend until September. Soil respirations ranged from 106 to 237 mg C m^{-2} hr^{-1} in forests and from 60 to 236 mg C m^{-2} hr^{-1} in dry grasslands. Soil respiration in the middle grassland plot reached to its maximum (30 to 234 mg C m^{-2} hr^{-1}) and was larger than that in forests and dry grasslands in July. On the other hand, it was smaller than that in forests and dry grasslands in June, August, and September. (Fig. 5).

The microbial respiration (CO_2 flux from bare soil plot) of all observed sites was 20-30% smaller than the soil respiration at each site (Fig. 5). A cumulative soil respiration (mean ± SD) was higher in forests (3.66 ± 0.383 Mg C ha^{-1}) than in dry and middle grasslands (2.62 ± 0.517 and 3.01 ± 0.196 Mg C ha^{-1}, respectively) (Table 2). The cumulative microbial respiration for forest, dry and middle grasslands were estimated as 2.86 ± 0.100, 1.81 ± 0.257 and 1.89 ± 0.271 Mg C ha^{-1} respectively (Table 2). The proportion of microbial respiration to total soil respiration was 78.1, 69.1, and 62.8% for forest, dry grassland and middle grassland, respectively.

Grassland NPP

The maximum above-ground biomass C was observed in July, before the harvesting of hay. The maximum below-ground biomass C in both grasslands was observed in August (Table 3). The above-ground biomass C was smaller than that of below-ground in both grasslands. The above-ground biomass C in dry and middle grasslands accounted for 17-19% and 30-54% of that of below-ground, respectively.

The maximum above-ground net primary production (ANPP) was observed during the period July-August in the dry grassland. While in the middle grassland, it was observed in the June-July period. Greater roots grew in the dry grassland during June-July. In the middle grassland within the period of June-July, the root mass underwent mineralization, which decreased after the heavy rains of August and September. During the July-August period, the below-ground net primary production (BNPP) of middle grassland became positive, while it was negative during the warm June-July period (Table 4). The average value of total NPP during the warm period of 2006 was estimated at 2.23 and 1.31 Mg C ha^{-1} for dry and middle grasslands, respectively (Table 4).

Grassland NEP and NBP

The NEP was positive in the dry grassland (0.317 Mg C ha^{-1}, $period^{-1}$), while negative in the middle grassland (-0.581 Mg C ha^{-1}, $period^{-1}$) (Table 5). This is the evidence of C loss from this grassland ecosystem in natural condition in absence of human activities. The actual hay harvest of farmers amounted to 0.258 and 0.631 Mg C ha^{-1} in dry and middle grasslands, respectively. The total area of the hay-harvested plot was estimated as 34 ha. The NBP of both grasslands was calculated taking into account harvested hay subtracted from the NEP. The NBP was estimated as 0.162 and -1.21 Mg C ha^{-1} during the observation period (86 days) for dry and middle grasslands, respectively (Table 5). It appeared in general that human activity was one of the most important factors that could change the soil C stock in grassland ecosystems.

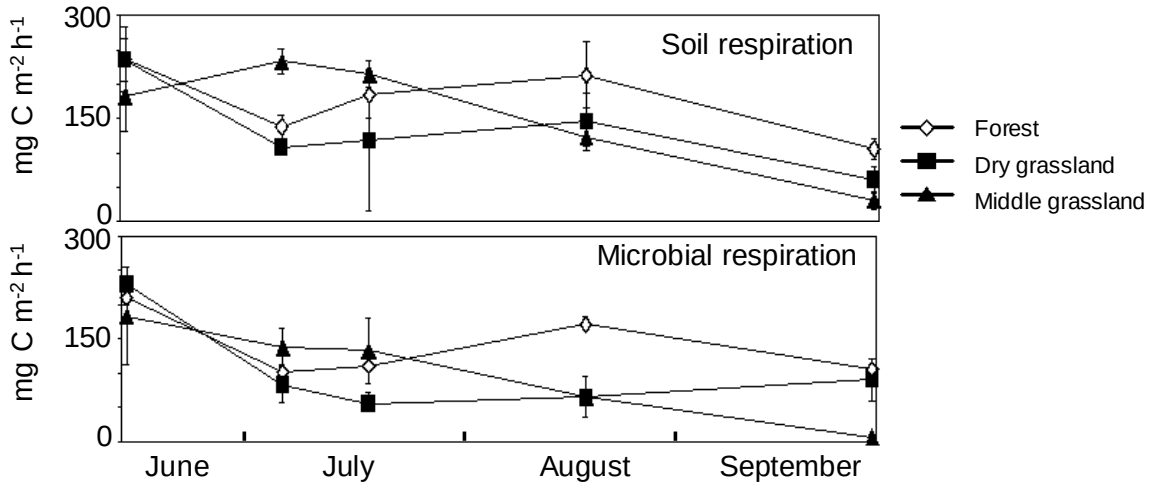

Fig. 5. Seasonal dynamics of soil and microbial respiration. Error bars indicate standard deviations.

Table 2. Cumulative soil and microbial respirations from each site along the forest-Alas transect.

		Forest	Dry grassland	Middle grassland
Soil respiration	Mg C ha^{-1}	3.66±0.383	2.62±0.517	3.01±0.196
Microbial respiration	Mg C ha^{-1}	2.86±0.100	1.81±0.257	1.89±0.271

Table 3. Biomass carbon in Alas grassland.

Plot		Biomass Carbon (Mg C ha^{-1})			
		21st June	21st July	17th August	17th September
Dry grassland	Above ground	0.454±0.093	0.766±0.433	0.990±0.340	0.430±0.146
	Below ground	2.53±0.126	3.89±1.230	4.22±0.0428	ND
Middle grassland	Above ground	1.08±0.266	1.89±0.284	1.18±0.0860	0.512±0.043
	Below ground	3.43±0.280	3.50±0.443	3.81±0.225	ND

Numbers are mean values and standard deviations.

Table 4. NPP of Alas grasslands.

Plot		NPP (Mg C ha^{-1})			
		June-July	July-Aug	Aug-Sept	Total
Dry grassland	Above ground	0.282	0.306	0.0429	2.23
	Below ground	1.30	0.301	ND	
Middle grassland	Above ground	0.804	0.240	0.0609	1.31
	Below ground	-0.0248	0.227	ND	

Table 5. NEP and NBP calculation of Alas grasslands during the observation period (86 days).

Plot	NPP (Mg C ha^{-1})	Microbial respiration (Mg C ha^{-1})	Yield (Mg C ha^{-1})	NEP (Mg C ha^{-1})	NBP (Mg C ha^{-1})
Dry grassland	2.23	1.81	0.258	0.420	0.162
Middle grassland	1.31	1.89	0.631	-0.581	-1.21

Discussion

Carbon storage in soils

Matuura *et al.* (1994) conducted a soil profile survey in another Alas (Unakh Alas) and an adjacent forest located 6 km north-east from the Alas we studied. They showed that soil C storage in active layer (permafrost thawing layer) was 64.6 Mg C ha^{-1} in 0-96cm layer in forest, 163 Mg C ha^{-1} in 0-260cm layer in dry grassland, 305 Mg C ha^{-1} in 0-137cm layer in middle grassland, and 656 Mg C ha^{-1} in 0-80cm layer in wet grassland. It reveals that dry, middle, and wet grasslands contained 2.5 times, 4.7 times and 10.2 times larger amount of soil C than forest, respectively. In this study, soil C storage in 0-40cm topsoil of the forest was 49.7 Mg C ha^{-1}, which was similar to the result from Matuura *et al.* (1994), although soil thickness in our study was less than that in the previous study. This indicates that soil C concentrates in the upper layer in forests. The middle grassland in thermokarst depression stored soil C 4.3 times larger than the forest, but the soil C storage of dry grassland had been reduced to 19.1% of the forest. This result indicates that those grasslands might store C in much deeper layer. However, it seems that the dry grassland lost its C more intensively than the middle grassland.

Short-term C balance in Alas grassland

Human activities such as grazing and hay harvest strongly reduce the share of the NPP that can be accumulated in the ecosystem (Parsons *et al.* 1983). The NBP in this study was estimated at 0.162 and -1.21 Mg C ha^{-1} during the observation period (86 days) for dry and middle grasslands, respectively. It indicates that thermokarst depression's middle grasslands showed a significant C loss, while dry grassland showed C sequestration. In other locations of cold temperate and boreal grasslands, fluctuation of C balance mainly depended on grassland management practice (Table 6). At Switzerland agricultural grasslands, the intensive management (manure and fertilizer application) field exhibited a C sequestration of 1.47 Mg C ha^{-1} year^{-1}, whereas the extensive field (no application of manure and fertilizer) showed a C loss of -0.570 Mg C ha^{-1} year^{-1} (Ammann *et al.* 2007). It shows that intensively managed grassland's NPP becomes higher than extensively managed. Alas grassland belongs to

Table 6. Carbon balance in different boreal grasslands.

Lat. & Longi.	Country	Grassland type	Carbon balance (Mg C ha^{-1})	Reference
47º17'N, 7º44'E	Switzerland	Intensive management, hay	1.47	Ammann et al. 2007
47º17'N, 7º44'E	Switzerland	Extensive management, hay	-0.570	Ammann et al. 2007
49º43'N, 112º56'W	Canada	Mixed grass prairie,	1.05	Shwalm et al. 2006
49º43'N, 112º56'W	Canada	Mixed grass prairie,	1.46	Flanagan et al. 2002
52º97'N, 105º45'W	Canada	Hay harvest	0.700	Mensah et al. 2003
62º09'N, 130º31' E	**Yakutia, Russia**	**Alas, dry grassland, hay harvest**	**0.162**	**this study**
62º09'N, 130º31' E	**Yakutia, Russia**	**Alas, middle grassland, hay harvest**	**-1.21**	**this study**

extensively managed grassland. Therefore, there are possibilities that alas grassland is a carbon source same as the previous reports. Mensah *et al*. (2003) reported a mean C sequestration rate of 0.60–0.80 Mg C ha^{-1} $year^{-1}$ from a managed forage field in Canada. The C sequestration rates of Canadian mixed grass prairies were 1.05 Mg C ha^{-1} $period^{-1}$ (June-September) (Schwalm *et al.* 2006) and 1.45 Mg C ha^{-1} $period^{-1}$ (June-August) (Flanagan *et al.* 2002). This difference between positive and negative C budgets can be explained firstly by the severe boreal climatic conditions of Central Yakutia compared with the other regions. Therefore, despite the relatively low NPP, soils of Alas ecosystem sequestrate a large amount of soil organic matter due to the relatively low rates of decomposition and larger fraction of plant debris derived from root turnover. And secondly, the difference can also be explained by human activities which are in extensive way in East Siberia.

This study was conducted during only one growing season, and we need to obtain data on different weather conditions, because the weather in year 2006 was not common rather abnormal due to a huge amount of precipitation in the summer. On the other hand, the data suggested that we should consider more weather condition, especially rainfall during the warm season. Because in closed Alas ecosystem, it plays a significant role in balancing water inside the thermokarst depression, consequently in C accumulation and greenhouse gas fluxes.

Conclusion

The utilization of thermokarst depression as pastures, in which grazing and hay harvest are conducted, might reduce soil C stock in thermokarst depressions. This case study showed that the grassland area having larger soil C storage reduced more C and showed negative NEP and NBP in grasslands with larger soil C storage than that in boreal forests, which is the net sink of atmospheric C. It shows that in global warming scenario, boreal forests may turn into a significant source of C during the thermokarst expansion.

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