

# Impact of soil temperature and soil moisture on GHG fluxes from an Eastern Siberian Taiga soil at Yakutsk, Russia

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## 1. INTRODUCTION

Forests are an important component of terrestrial biomes. Forest biomass contains more than 85% of the carbon stored by terrestrial vegetation, and forest soils make up more than 70% of the world's soil carbon pool (Post et al. 1982; Cao and Woodward 1998). High latitude forests contain 49% of the world's forest carbon, of which 58% is in Russia (Dixon et al. 1994). A vast area in eastern Siberia is covered by a unique Taiga forest of deciduous larch trees (*Larix gmelinii*), which is established at a continuous permafrost. The amount of precipitation in eastern Siberia is extremely small (Kobak et al. 1996), and permafrost plays an important role for the water cycle in this area as a buffer for transpiration (Sugimoto et al. 2002).

However, climate-change scenarios predict an increase in average global temperature of 1.4-5.8°C and in average global precipitation of 3-15% in the next century and the change will be most pronounced in high latitudes (IPCC 2001). These changes will alter the climatic condition in the cold and dry soils of Siberian Taiga forests. Generally, the change in soil climatic condition due to the change in climate may affect the relationship between GHGs and soils, resulting negative feedback to the global warming. Based on a review of *in situ* measurements, the Q<sub>10</sub> value (relative increase in activity after an increase of 10°C temperature) for total soil respiration had a median value of 2.4 (Raich and Schlesinger 1992). Soil moisture also influences the rate of soil respiration (Orchard and Cook 1983; Keith et al. 1997). The strength of CH<sub>4</sub> sink is affected by soil moisture both through restricting CH<sub>4</sub> diffusion as well as regulating CH<sub>4</sub> consumption (Castro et al. 1994; Le Mer and Roger 2001). Temperature, on the other hand, appears to have a less important control on CH<sub>4</sub> consumption from the atmosphere (Castro et al. 1994; Whalen and Reebutgh 1996). N<sub>2</sub>O production increases with increase in soil moisture and soil temperature (Sitaula and Bakken 1993; Schindlbacher et al. 2004). In the eastern Siberian Taiga forest, cold and dry soil conditions and a greater change in future climate may allow a greater change in GHG flux than other forest ecosystems (Bunnell and Tait 1974; Schleser 1982; IPCC 2001). However, there is a very few study of soil GHG fluxes in east-Siberian Taiga forests (e.g. Sawamoto et al. 2000, 2003; Morishita et al. 2003) so that the response of the GHG fluxes to the change in soil condition in Siberian Taiga forest on permafrost is extremely unclear.

The objective of this study was therefore to evaluate the effect of change in soil climate on GHG fluxes of a Siberian Taiga forest ecosystem at Yakutsk in eastern Siberia. Although the real effect of temperature and precipitation on GHGs in fields is difficult to evaluate because of its complicated operation on the soil climate, some studies reported direct effects of soil drought and rewetting on GHG fluxes from the soil (Peterjohn et al. 1994; Borken et al. 1999,

2000, 2003; Davidson et al. 2004). We applied irrigation on the forest floor directly and evaluated the impact of soil temperature and moisture conditions on the GHG fluxes.

## 2. MATERIALS AND METHODS

### 2.1 Site description

The study site is a larch forest on sandy soil (Typic Psammenturbels) in Spasskaya Pad experimental forest (62°15' N, 129°37' E) of the Institute for Biological Problems of Cryolithozone, near Yakutsk, Republic of Sakha, Russia. Larch trees (*Larix gmelinii*) occupy 98% of the total basal area of tree trunks of the forest. The stand density (number of larch trees above breast height) of the forest is 836 trees ha<sup>-1</sup> (Sugimoto et al. 2002). The forest floor is covered by shrubby vegetations including *Vaccinium vitis-idaea* and *Arctous erythrocarpa*. The thickness of the forest floor is about 10 cm. Forest fires occurred about 70 years ago and the surface of the forest floor was burned. The mean annual temperature is -10.0°C with the lowest mean temperature in January at -41.2°C and the highest mean temperature in July at 18.7°C. The mean annual precipitation is recorded to be 237 mm (National Astronomical Observatory 1998).

Two 0.256 ha plots, one is for control (CT) and the other is manipulated by irrigation (IR), were established at an interval of 50 m in order to minimize the effect of irrigation in the IR plot on the biogeochemical cycle in the CT plot (Fig. 1). In order to estimate microbial respiration, 4 root-cut small areas of 0.64 m<sup>2</sup> were established in each of IR and CT plots in July 2003. Kajimoto et al. (2003) reported that the lateral root of *Larix gmelinii* was distributed within upper soils (<20 cm) and rarely grew into deeper soils (>15 cm). Therefore, a 30 cm deep trench was made surrounding the area, then the soil column was immediately lapped with a vinyl sheet and the trench was filled with the soil. Herbs and shrubs were removed from the root-cut plots.

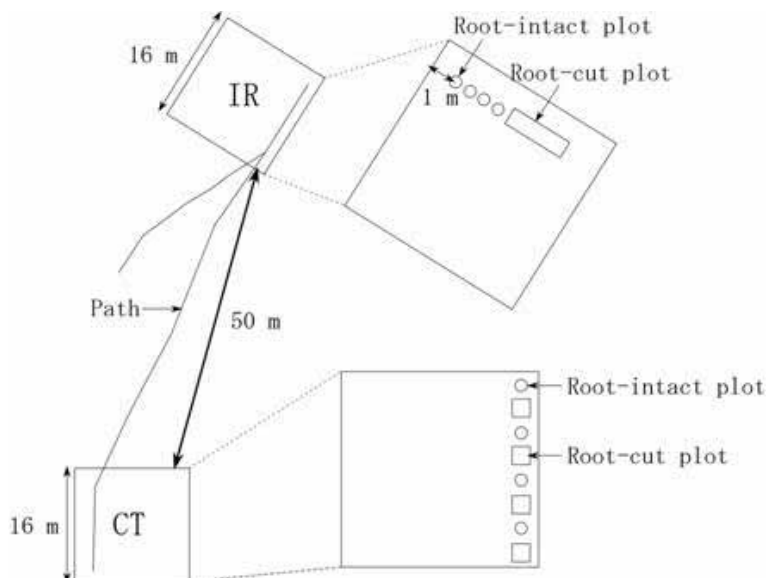


Fig. 1. Layout of the study site

An artificial irrigation was carried out from 17 to 22 July 2004. Before starting the irrigation, we constructed a pathway for walking by placing small wooden planks to minimize disturbance of forest floor. The irrigation was accomplished by using a rubber hose from approximately 1.5 m height. Therefore, the irrigation alleviated soil dryness but did not alter atmospheric moisture in the canopy. The irrigation of 20 mm per day was conducted everyday, which is equal to the amount of the mean precipitation during the summer season. Lena River water was used for the irrigation.

## 2.2 Measurement of soil and microbial respirations

Soil respiration was measured using a closed chamber technique (four replications per plot) from 1st to 23rd July 2004. During the irrigation period, we did not carry out any measurements within eight hours after the irrigation to avoid instability of soil condition. Stainless steel cylinders (19.0-20.5 cm in diameter and 25 cm height) were installed at 5 cm depth into the soil. All plants inside the cylinders were removed carefully to exclude plant respiration. Before the measurements, the air inside the cylinders was transferred into Tedlar<sup>R</sup> Bags. Air temperature was measured with a digital thermometer. During the measurements, acrylic lid was put on the cylinder. Soil temperature was also measured with a digital thermometer at a depth of 10 cm and soil moisture was measured as volumetric water content with a TDR (TRIME-como; Tohoku Electronic Industrial Co. Ltd., Sendai, Japan) at a depth of 0 to 10 cm (four replications). Six minutes later, the air inside the chambers was taken out. The CO<sub>2</sub> concentration of gas inside the Tedlar<sup>R</sup> Bag was determined with a portable infrared CO<sub>2</sub> gas analyzer (ZFP9GC11; Fuji Electric systems Co. Ltd., Tokyo, Japan). Fluxes were calculated based on the variations in CO<sub>2</sub> concentrations inside the chamber with time, by using a linear regression method (Hu et al. 2004; Nakano et al. 2004). The CO<sub>2</sub> flux from root-cut areas (microbial respiration) was measured in the same day as soil respiration measurements, which was assumed as microbial respiration.

To evaluate the effect of soil temperature and soil moisture on soil and microbial respirations separately, we performed multiple regressions between the logarithm of soil and microbial respirations and the reciprocals of soil temperature and soil moisture by applying Arrhenius equations as the following equation:

$$\ln(\text{CO}_2 \text{ flux}) = a_T * (1/T) + a_W * (1/W) + b \quad (1)$$

where T is soil temperature at 10 cm depth of the soil at time of sampling and W is soil moisture in the top 0 to 10 cm. We also calculated Q<sub>10</sub> values to estimate effects of soil temperature and moisture on soil and microbial respiration as the following equations:

$$Q_{10T} = e^{-a_T * (1/273 - 1/283)} \quad \text{and} \quad Q_{10W} = e^{-a_W * (1/10 - 1/20)} \quad (2)$$

where Q<sub>10T</sub> is the increase in the rate of CO<sub>2</sub> emission with increase in soil temperature from 0 to 10°C and Q<sub>10W</sub> is the increase in the rate of CO<sub>2</sub> emission with increase in soil moisture from 0.1 m<sup>3</sup> m<sup>-3</sup> to 0.2 m<sup>3</sup> m<sup>-3</sup>.

## 2.3 CH<sub>4</sub> and N<sub>2</sub>O Flux measurement

A closed chamber technique was also used for the measurement of CH<sub>4</sub> and N<sub>2</sub>O fluxes from the soil. At 0, 30, and 60 minutes after the chamber was closed with a lid, a 20-mL air sample inside the chamber was taken into a 10-mL glass bottle vacuum-sealed with a butyl rubber stopper and a plastic cap. The CH<sub>4</sub> and N<sub>2</sub>O flux measurements were carried out 10 minutes after the CO<sub>2</sub> flux measurement. CH<sub>4</sub> and N<sub>2</sub>O concentrations of the air samples were analyzed with a gas chromatograph (GC). The GC used for analyzing CH<sub>4</sub> concentrations was equipped with a flame ionization detector (GC-8A; Shimadzu, Kyoto, Japan) and for analyzing N<sub>2</sub>O concentrations was equipped with an electron capture detector (GC-14B; Shimadzu, Kyoto, Japan). Gas fluxes were calculated based on the variations in the CH<sub>4</sub> and N<sub>2</sub>O concentration inside the chamber with time, by using a linear regression method. Negative fluxes represent

uptake of gases by soil (Morishita et al. 2004; Yanai et al. 2003).

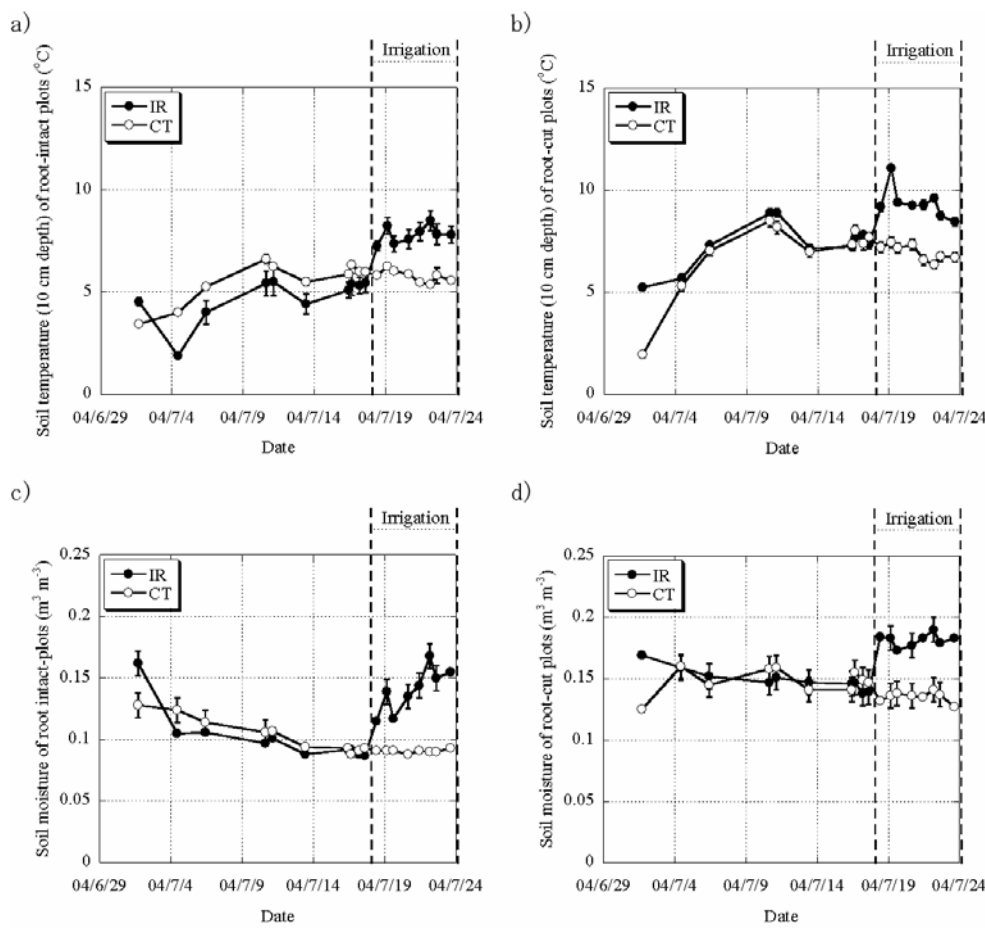
2.4 Statistical analysis

The statistical difference between the data measured before the irrigation and during the irrigation was determined by two-sided Mann-Whitney’s U test. The difference at 5% level was considered significant.

3. RESULTS

3.1 Temporal variation in soil climatic condition

Soil temperature in IR plot significantly increased to  $7.81 \pm 0.42^{\circ}\text{C}$  during the period of irrigation from  $4.70 \pm 1.11^{\circ}\text{C}$  during the period before irrigation (Fig. 2a, Table 1). However, the soil temperature in CT plot was almost stable, which was  $5.53 \pm 1.04^{\circ}\text{C}$  before irrigation and  $5.77 \pm 0.29^{\circ}\text{C}$  after irrigation.



**Fig. 2.** Temporal variation in soil temperature at 10 cm depth (a, b) and soil moisture of 0 – 10 cm soil (c, d) of the root-intact and the root-cut plots. The closed and open circles represent the data of IR and CT plots, respectively. Vertical bars denote standard error of each parameter.

Soil temperature in root-cut areas showed a similar behavior to that in root-intact areas. Soil temperature in root-cut areas of IR plot significantly increased to  $9.37 \pm 0.78^\circ\text{C}$  during the irrigation period from  $7.73 \pm 1.17^\circ\text{C}$  before irrigation, while the soil temperature in root-cut areas of CT plot did not change, which was  $6.85 \pm 1.93^\circ\text{C}$  during the irrigation and  $6.95 \pm 0.40^\circ\text{C}$  before irrigation. These results indicate that soil temperature in IR plot increased due to the irrigation (Fig. 2b, Table 2).

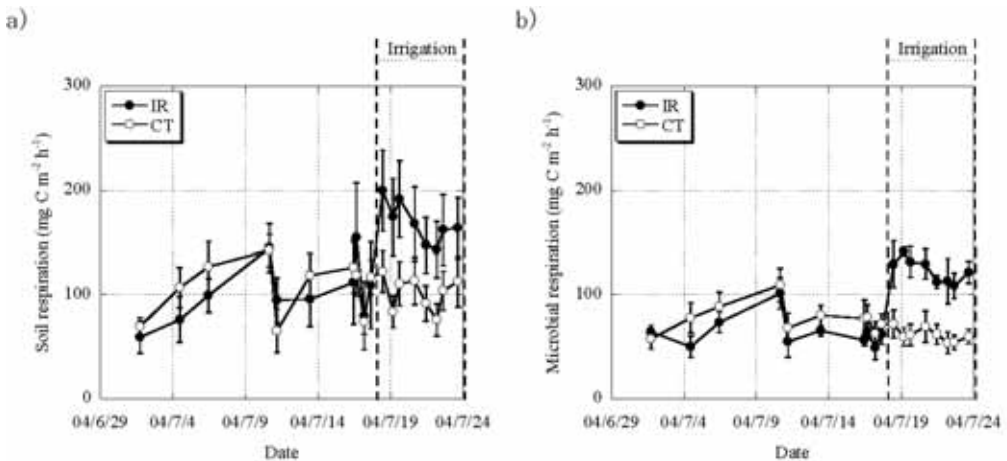
Soil moisture in IR plot significantly increased from  $0.102 \pm 0.022 \text{ m}^3 \text{ m}^{-3}$  before irrigation to  $0.140 \pm 0.018 \text{ m}^3 \text{ m}^{-3}$  during the irrigation (Fig. 2c, Table 1). On the other hand, soil moisture in CT plot significantly decreased from  $0.104 \pm 0.014 \text{ m}^3 \text{ m}^{-3}$  before irrigation to  $0.0908 \pm 0.0014 \text{ m}^3 \text{ m}^{-3}$  during the irrigation. Soil moisture in root-cut areas of IR plot significantly increased from  $0.149 \pm 0.009 \text{ m}^3 \text{ m}^{-3}$  before irrigation to  $0.181 \pm 0.005 \text{ m}^3 \text{ m}^{-3}$  during the irrigation, while soil moisture in root-cut areas of CT plot significantly decreased from  $0.148 \pm 0.011 \text{ m}^3 \text{ m}^{-3}$  before irrigation to  $0.135 \pm 0.004 \text{ m}^3 \text{ m}^{-3}$  during the irrigation (Fig. 2d, Table 2). These results suggest that the soil moisture in IR plot increased due to the irrigation while the soil in CT plot kept drying during the whole period of this experiment.

The average increase in soil temperature and soil moisture in root-intact areas in IR plot was  $3.11^\circ\text{C}$  and  $0.038 \text{ m}^3 \text{ m}^{-3}$ , respectively. An increase of  $0.038 \text{ m}^3 \text{ m}^{-3}$  in soil moisture could be resulted by only 3.8 mm irrigation. This means that the daily 20 mm irrigation is enough to keep the soil wet during the irrigation period.

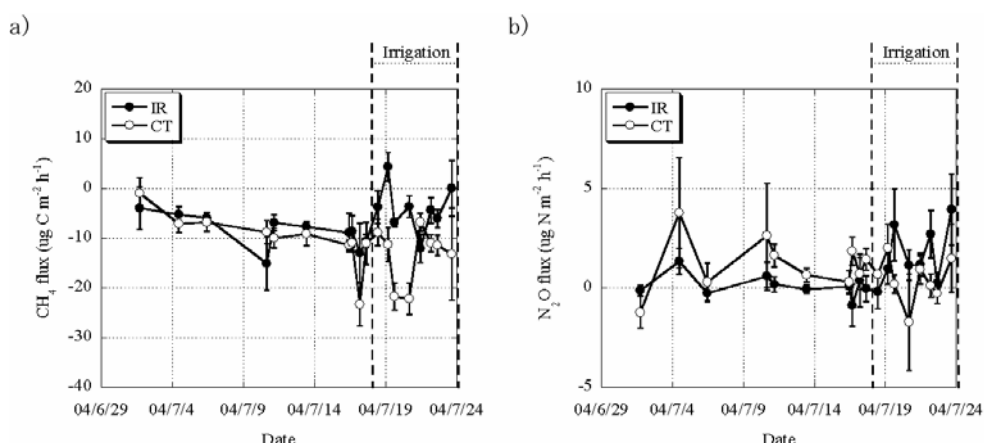
### 3.2 Response of soil and microbial respirations to the irrigation

Both soil respiration (root intact) and microbial respiration (root cut) increased immediately just after the irrigation (Fig. 3). Soil respiration in IR plot significantly increased to  $169 \pm 20 \text{ mg C m}^{-2} \text{ h}^{-1}$  during the irrigation from  $103 \pm 29 \text{ mg C m}^{-2} \text{ h}^{-1}$  before irrigation (Fig. 3a, Table 1). On the other hand, soil respiration in CT plot did not increase, which was  $107 \pm 27 \text{ mg C m}^{-2} \text{ h}^{-1}$  before irrigation and  $102 \pm 16 \text{ mg C m}^{-2} \text{ h}^{-1}$  during the irrigation.

Microbial respiration in IR plot significantly increased from  $64.3 \pm 15.1 \text{ mg C m}^{-2} \text{ h}^{-1}$  before irrigation to  $123 \pm 11 \text{ mg C m}^{-2} \text{ h}^{-1}$  during the irrigation, while microbial respiration in CT plot significantly decreased from  $77.3 \pm 14.5 \text{ mg C m}^{-2} \text{ h}^{-1}$  before irrigation to  $61.6 \pm 6.4 \text{ mg C m}^{-2} \text{ h}^{-1}$  during the irrigation (Fig. 3b, Table 2).



**Fig. 3.** Temporal variation in soil respirations (a) and microbial respirations (b) of IR (closed circle) and CT plot (open circle). Vertical bars denote the standard error of each parameter.



**Fig. 4.** Temporal variations in CH<sub>4</sub> (a) and N<sub>2</sub>O fluxes (b) of IR (closed circle) and CT plot (open circle). Vertical bars denote standard error of each parameter.

**Table 1.** Observed values of the parameters in the root-intact plots.

|  |           | Before irrigation | During irrigation | P     |
|--|-----------|-------------------|-------------------|-------|
| Soil temperature<br>(°C)   | Irrigated | 4.70 ± 1.11       | 7.81 ± 0.42       | 0.000 |
|  | Control   | 5.53 ± 1.04       | 5.77 ± 0.29       | 0.528 |
| Soil moisture<br>(m <sup>3</sup> m <sup>-3</sup> )               | Irrigated | 0.102 ± 0.022     | 0.140 ± 0.018     | 0.001 |
|  | Control   | 0.104 ± 0.014     | 0.0908 ± 0.0014   | 0.022 |
| Soil respiration<br>(mg C m <sup>-2</sup> h <sup>-1</sup> )      | Irrigated | 103 ± 29          | 169 ± 20          | 0.000 |
|  | Control   | 107 ± 27          | 102 ± 16          | 0.664 |
| CH <sub>4</sub> flux<br>(μg C m <sup>-2</sup> h <sup>-1</sup> )  | Irrigated | -8.61 ± 3.47      | -4.08 ± 4.83      | 0.034 |
|  | Control   | -9.96 ± 5.62      | -13.3 ± 5.7       | 0.226 |
| N <sub>2</sub> O flux<br>(μg N m <sup>-2</sup> h <sup>-1</sup> ) | Irrigated | 0.111 ± 0.580     | 1.64 ± 1.47       | 0.008 |
|  | Control   | 1.20 ± 1.39       | 0.422 ± 1.144     | 0.221 |

**Table 2.** Observed values of the parameters in the root-cut plots.

|  |           | Before irrigation | During irrigation | P     |
|--|-----------|-------------------|-------------------|-------|
| Soil temperature<br>(°C)   | Irrigated | 7.73 ± 1.17       | 9.37 ± 0.78       | 0.001 |
|  | Control   | 6.85 ± 1.93       | 6.95 ± 0.40       | 0.883 |
| Soil moisture<br>(m <sup>3</sup> m <sup>-3</sup> )               | Irrigated | 0.149 ± 0.009     | 0.181 ± 0.005     | 0.000 |
|  | Control   | 0.148 ± 0.011     | 0.135 ± 0.004     | 0.007 |
| Microbial respiration<br>(mg C m <sup>-2</sup> h <sup>-1</sup> ) | Irrigated | 64.3 ± 15.1       | 123 ± 11          | 0.000 |
|  | Control   | 77.3 ± 14.5       | 61.6 ± 6.4        | 0.012 |

Both soil and microbial respirations increased by about 60 mg C m<sup>-2</sup> h<sup>-1</sup> instantly after applying irrigation (Fig. 3). The similar rate increment in soil and microbial respirations were found by Borken et al. (2003). The integrated soil respiration during the irrigation in IR and CT

plots were 209 and 127 kg C ha<sup>-1</sup>, respectively (Table 3). This indicates that the irrigation increased the soil respiration by 1.65 times. The integrated microbial respiration in IR and CT plots were 154 and 77 kg C ha<sup>-1</sup>, respectively, indicating that the irrigation increased the microbial respiration by 2.0 times. On the other hand, the integrated root respiration, calculated as the difference between soil respiration and microbial respiration in IR and CT plots, were 55 and 50 kg C ha<sup>-1</sup>, respectively, suggesting that the irrigation affect was smaller in the root respiration. These results suggest that the increase in soil respiration was mainly due to the increase in microbial respiration rather than root respiration.

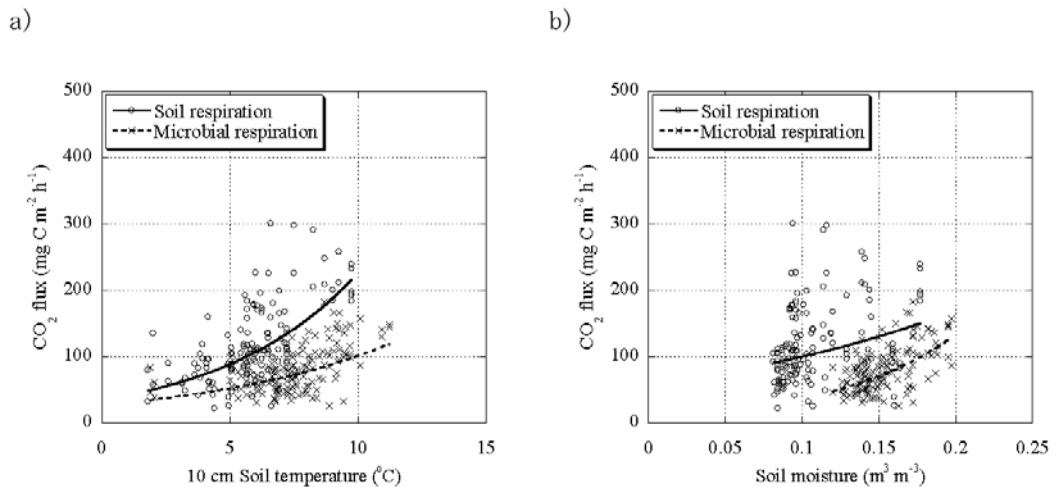
Soil and microbial respiration rates exponentially increased with an increase in soil temperature and soil moisture (Fig. 5). An increase in soil temperature increased the rate of soil respiration greater than that of microbial respiration (Fig. 5a). On the other hand, the increase in soil moisture increased the rate of soil respiration less than that of the microbial respiration (Fig. 5b).

The multiple regression equations of soil and microbial respirations are as follow:

$$\ln(\text{soil resp.}) = -5160 * (1/T) - 21.9 * (1/W) + 24.2 \quad (r^2 = 0.38; p < 0.001) \quad (3)$$

$$\ln(\text{microbial resp.}) = -14200 * (1/T) - 0.991 * (1/W) + 55.5 \quad (r^2 = 0.34; p < 0.001) \quad (4)$$

Substituting the values of regression coefficients (at and aw) of Eqs. (3) and (4) into Eq. (2), Q<sub>10t</sub> values of soil and microbial respirations became 6.25 and 1.95, respectively, and Q<sub>10w</sub> values of soil and microbial respirations were 1.05 and 2.99, respectively (Table 4).



**Fig. 5.** Relationship between soil CO<sub>2</sub> flux and soil temperature at 10 cm depth (a) and soil moisture (b).

**Table 3.** CO<sub>2</sub> emission by soil and microbial respiration in IR and CT plot during the period of irrigation (kg C ha<sup>-1</sup>). Root respiration was calculated as the difference between soil respiration and microbial respiration. Increase rates were calculated by dividing CO<sub>2</sub> emissions in IR plot by those in CT plot.

|                       | IR  | CT  | Increase rate |
|-----------------------|-----|-----|---------------|
| Soil respiration      | 209 | 127 | 1.65          |
| Microbial respiration | 154 | 77  | 2.00          |
| Root respiration      | 55  | 50  | 1.10          |

**Table 4.** The  $Q_{10}$  values for the relationship between  $\text{CO}_2$  flux and soil temperature or soil moisture.

|                       | $Q_{10t}$ | $Q_{10w}$ |
|-----------------------|-----------|-----------|
| Soil respiration      | 6.25      | 1.05      |
| Microbial respiration | 1.95      | 2.99      |

**Note:**  $Q_{10}$  values were obtained from the multiple regressions  $\ln(\text{CO}_2 \text{ flux}) = at^*(1/T) + aw^*(1/W) + b$ , where  $Q_{10t} = e^{-at^*(1/273-1/283)}$ ,  $Q_{10w} = e^{-aw^*(1/10-1/20)}$ ,  $T$  is the soil temperature, and  $W$  is the soil moisture.

### 3.3 Response of $\text{CH}_4$ and $\text{N}_2\text{O}$ fluxes to irrigation

$\text{CH}_4$  flux was almost negative in both IR and CT plots. Negative  $\text{CH}_4$  flux means that  $\text{CH}_4$  was taken up by soil. The  $\text{CH}_4$  flux in IR plot significantly increased from  $-8.61 \pm 3.47 \mu\text{g C m}^{-2} \text{ h}^{-1}$  before the irrigation period to  $-4.08 \pm 4.83 \mu\text{g C m}^{-2} \text{ h}^{-1}$  during the irrigation (Table 1, Fig. 4a).  $\text{CH}_4$  flux in CT plot did not increase, which was  $-9.96 \pm 5.62 \mu\text{g C m}^{-2} \text{ h}^{-1}$  before irrigation and  $-13.3 \pm 5.7 \mu\text{g C m}^{-2} \text{ h}^{-1}$  during the irrigation. These results indicate that the irrigation decreased soil  $\text{CH}_4$  uptake.  $\text{CH}_4$  flux was not correlated with soil temperature ( $P > 0.05$ ) but was correlated with soil moisture ( $P < 0.001$ ).

$\text{N}_2\text{O}$  flux was also influenced by the irrigation.  $\text{N}_2\text{O}$  flux in IR plot significantly increased from  $0.111 \pm 0.580 \mu\text{g N m}^{-2} \text{ h}^{-1}$  before the irrigation period to  $1.64 \pm 1.47 \mu\text{g N m}^{-2} \text{ h}^{-1}$  during the irrigation (Table 1, Fig. 4b).  $\text{N}_2\text{O}$  flux in CT plot did not increase, which was  $1.20 \pm 1.39 \mu\text{g N m}^{-2} \text{ h}^{-1}$  before irrigation and  $0.422 \pm 1.144 \mu\text{g N m}^{-2} \text{ h}^{-1}$  during the irrigation.  $\text{N}_2\text{O}$  flux was correlated with both soil temperature ( $P < 0.05$ ) and soil moisture ( $P < 0.05$ ).

## 4. DISCUSSION

The  $Q_{10t}$  value of the soil respiration (Table 4) was much higher than the published values ranging from 1.3 to 3.3 (Raich and Schlesinger 1992). On the other hand, the  $Q_{10t}$  value of the microbial respiration (Table 4) was similar to the published values of 2.5 (Boone et al. 1998). It is known that  $Q_{10t}$  of root respiration may vary depending on the range of temperature over which it is determined (Ryan 1991), with higher values of  $Q_{10t}$  occurring when low temperature ranges are examined. Kirschbaum (1995) reported that  $Q_{10t}$  values of microbial respiration could also vary depending on the range of temperatures in low temperature areas. The high value of the soil respiration seems to occur by the low temperature of the investigated soil. On the other hand, Carlyle and Ba Than (1988) found that two models, using soil moisture and temperature to predict soil respiration, overestimated soil  $\text{CO}_2$  fluxes in a *Pinus radiata* stand in Australia because extremely dry conditions limited the microbial response to temperature variation. The similar  $Q_{10t}$  value of the microbial respiration in the low temperature to the published value seems to occur by the low range of soil moisture of the investigated soil.

The lower  $Q_{10w}$  value of the soil respiration than that of the microbial respiration (Table 4) indicated that the root respiration was suffered by the negative effect from the soil moisture. Moog and Bruggemann (1998) reported that root respiration rates decreased when plants were precultured anaerobically in flooding sensitive plants, while in flooding tolerant plants preculture conditions had no effect on root  $\text{CO}_2$  release. The larch trees at the site can be flooding sensitive because of the dry climate in Yakutsk, causing the negative impact of the root respiration to the increase in soil moisture.

The similar  $\text{CO}_2$  emission by the root respiration between IR and CT plots ( $55$  and  $50 \text{ kgC ha}^{-1}$ , respectively; Table 3) suggests that the increase in the soil respiration rate in IR plot due to



the irrigation was resulted by the increase in the microbial respiration. The microbial respiration increased by 2.00 times due to the irrigation while the soil respiration increased by 1.65 times (Table 3) despite the large difference between the  $Q_{10t}$  values of the soil and microbial respiration (Table 4). These results may suggest that an acceleration of the root respiration by the increase in soil temperature due to irrigation and a depression of the root respiration by the increase in soil moisture are occurring at once.

We calculated the actual increase in the rate of  $CO_2$  emission with increase in soil temperature and soil moisture due to the irrigation ( $Q_t$  and  $Q_w$ , respectively) as the following equation:

$$Q_t = e^{-at \times (1/T_i - 1/T_0)}, Q_w = e^{-aw \times (1/W_i - 1/W_0)} \quad (5)$$

where  $Q_t$  is the increase of the rate of  $CO_2$  emission with actual increase of soil temperature due to the irrigation,  $Q_w$  is the increase of the rate of  $CO_2$  emission with actual increase of soil moisture due to the irrigation,  $T_i$  and  $T_0$  are the soil temperature during the irrigation and before the irrigation, respectively, and  $W_i$  and  $W_0$  are the soil moisture during the irrigation and before the irrigation, respectively.  $Q_t$  and  $Q_w$  values of soil respiration was 1.76 and 1.03, respectively, and  $Q_t$  and  $Q_w$  values of microbial respiration was 1.12 and 1.30, respectively. The soil respiration including the root respiration seemed to be affected by the soil temperature, while the microbial respiration was mainly affected by the soil moisture.

As a result, we found that the root activity was affected by the soil temperature and the microbial activity was mainly affected by the soil moisture in this site. A greater influence of soil moisture to microbial respiration than of soil temperature is also reported in dry conditions (Carlyle and Ba Than 1988; Xu and Qi 2001). In general, an excessive supply of water to soil depresses the decomposition of organic matter in the soil (e.g. Gorham 1991). In this irrigation experiment, an equal amount of the mean precipitation during the summer season was applied. Analyzing response of GHG fluxes to higher water content in the soil needs further examination. Although root respiration is also reported to be affected by soil moisture in dry condition (Pregitzer et al. 2000; Lavigne et al. 2004), roots acclimated to water stress are reported to be much less sensitive to decline in soil moisture (Atkin et al. 2000). Larch trees in this site may be acclimated to dry condition so as not to show a positive correlation between the root respiration and soil moisture.

The  $CH_4$  flux decreased quickly as the irrigation was started (Fig. 4a). Generally,  $CH_4$  absorption rates decrease with increase in soil moisture because of alterations in gas transport (Castro et al. 1994) and decreases in aerobic zones in the soil (Le mer and Roger 2001). On the other hand, Striegl et al. (1992) reported that absorption of  $CH_4$  by desert soil was enhanced by rainfall. Despite the low range of precipitation, the response of  $CH_4$  flux to increase in soil moisture in the Siberian Taiga forest investigated was different from that in the desert. This suggests that the soil in the Taiga ecosystem investigated has enough water to keep methane consumption active.

The  $N_2O$  flux significantly increased during the irrigation period (Fig. 4b) and was correlated with both soil temperature ( $P < 0.05$ ) and soil moisture ( $P < 0.05$ ). The correlation between  $N_2O$  flux and soil temperature and moisture is also reported in other sites (Sitaula and Bakken 1993; Schindlbacher et al. 2004). However, the response of the  $N_2O$  flux to the irrigation was much less than that of the  $CO_2$  or  $CH_4$  fluxes (Figs. 3, 4). The Siberian Taiga ecosystem is reported to be short of available nitrogen (Schulze et al. 1995). The irrigation would increase decomposition rate of soil organic matter and N availability, which would eventually lead to greater change in N cycling in the forest ecosystem including an increased flux of  $N_2O$  caused by increased net N mineralization and net nitrification (Aber et al. 1989). A long term investigation would be required to observe a bigger change in N cycling due to irrigation.

## 5. CONCLUSION

A quick response of soil and microbial respirations along with CH<sub>4</sub> flux to the irrigation was observed in Taiga ecosystem investigated. The main cause of the increase in soil respiration was the increase in microbial respiration due to the increase in soil moisture, suggesting that a little precipitation would be able to much increase the soil respiration. On the other hand, the root respiration was suffered negative effect from the soil moisture. The decrease in CH<sub>4</sub> absorption rates during the irrigation suggested that the soil in the Taiga ecosystem investigated has enough water to keep methane consumption active. A little change in N<sub>2</sub>O flux due to the irrigation suggested that a long term investigation may be required to observe a bigger change in N cycling in the forest ecosystem associated with irrigation.

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