Estimation of annual soil respiration rate in a larch forest in Central Siberia

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Abstract
Soil respiration is an important component process of carbon cycle in terrestrial ecosystems. The forested area of the continuous permafrost zone of Central and Northeastern Siberia exceeds that of boreal forests in other regions of the world. However, soil respiration has rarely been studied in Siberia. We conducted soil respiration rate (SR) measurement during the three growing seasons (2005–2007) and in a mid-winter by using a closed-chamber technique in a typical mature *Larix gmelinii* forest in Central Siberia. We examined micro-scale variations of SR by comparing the three dominant types of forest floor vegetation (lichen and mosses); patches of *Cladina stellaris*, *Pleurozium schreberi*, and *Aulacomnium palustre*. The daily mean SR at each period differed among the types: the values throughout the observation period (mg C/m^2/h) was the highest in *Pleurozium* (21–110), followed by *Cladina* (17–85) and *Aulacomnium* (9–68). The SR was positively correlated with soil temperature. The lowest SR in the *Aulacomnium* patch was related to higher soil moisture and lower soil temperature than the other two patches. Estimated annual SR was apparently smaller in the larch forest of Siberia than those reported for any other boreal forests.

Key Words
CO_2 flux, global warming, Russia, Gelisol, hummock, hollow.

Introduction
Soil is the major carbon pool in terrestrial ecosystems (Schlesinger and Andrews 2000). Soil respiration (SR) is an important component process (Schlesinger and Andrews 2000) of carbon cycle. SR is positively related to soil temperature in northern hemisphere temperate ecosystems (eg. Hibbard *et al.* 2005). SR is also affected by soil moisture; very high soil moisture can block soil pores (Bouma and Bryla 2000) and very low soil moisture limits microbial and root respiration (Yuste *et al.* 2003). But, in some cases, SR is not related to soil moisture (eg. Palmroth *et al.* 2005). Boreal forest in Russia plays an important role in carbon storage (Rozhkov *et al.* 1996). Larch forest in Central Siberia was characterized by low temperature and precipitation, and the presence of permafrost. Furthermore, the ground surface was characterized by low earth hummock microtopography with various lichens and mosses. So, it is considered that both soil temperature and soil moisture are very important controller of soil respiration in the region. The purpose of this study was to elucidate the effect of soil temperature and moisture on the SR related to the difference of forest floor vegetation in a larch forest in Central Siberia.

Methods
Study site
The study was conducted in Tura (64° 12’ N, 100 ° 27’ E), Central Siberia at the beginning of June in2005 and 2007, middle of July in 2005 and 2007, beginning of August in 2006, beginning of September in 2005, 2006 and 2007, and middle of February in 2007. The annual mean temperature and precipitation are –9.2 °C and 334 mm, respectively (Robert 1997). Soil type is Gelisol with permafrost below the depth of 70 to 100 cm from the surface and poor drainage. The soil is frozen from mid– October to the end of May. The forest consists mainly of Larch (*Larix gmelinii*) trees about 100 years old. Patches of lichens and mosses, mainly *Cladina* sp., *Pleurozium* sp., and *Aulacomnium* sp., cover the forest floor with depth of 10 to 20 cm.

Measurements of soil respiration rate (SR)
SR was measured by using a closed chamber technique according to the method of Sawamoto *et al.* (2000). Six stainless steel chambers, 25 cm height and 20 cm in diameter, were used. Each two chambers were set on patches of *Cladina stellaris*, *Pleurozium shreberi*, and *Aulacomnium palustre*. Before the measurement of SR, green parts of plants on the forest floor were cut carefully in order to exclude plant respiration. And then, the chamber collars were installed at 5 cm depth into the soil and kept overnight to eliminate the disturbance. In the following day, each 500–mL gas sample was taken into a Tedlar® bag before the chamber lid was set

up and at 6 minutes after the lid was set up. The SR was measured three times in June, and nine times in July and September in a day. Soil temperature and moisture as a volumetric water content moisture by TDR (Hydorosense™, Campbel Scientific Australia Phy. Ltd.) were measured at a depth of 10 cm and 0–12 cm below the surface near the chambers, respectively. CO_2 concentrations in the bags were analysed by portable gas analyser (LI–820, LICOR). The SR was calculated according to the change in CO_2 concentrations in the chamber with time by using a linear regression law.

Statistical analysis

Mean temperatures, soil moistures, and SR in each patch were calculated from 6 to 18 measurements. Two–way analysis of variance followed by Fisher's test was used to compare the means. Multiple regression analysis was conducted to explain the SR using soil temperature and moisture. The stepwise method was used for the calculation. Excel Toukei (SSRI, Japan) was used for all statistical analysis.

Results and discussion

Seasonal changes of soil respiration

As for an example, daily change of soil temperature, moisture, and soil respiration in 2005 are shown in Figure 1. Soil temperatures in each patch were highest in July (max: 13.6 °C at *Pleurozium* patch), but the soil temperature in night time decreased almost equal to that in June and September. Soil temperature in the *Aulacomnium* patch was significantly lower than that in other patches in July (6.4 °C) and September (4.4 °C). Soil moistures in each patch were higher in September than that in July (Figure 1). Soil moisture in the *Aulacomnium* patch was significantly higher than that in other patches in both July (0.31 m^3/m^3) and September (0.38 m^3/m^3). Highest SR was observed in *Pleurozium* patch in July (181 mg $C/m^2/h$). Similar tendency of the daily change was observed in other measurements (not shown). There were significant differences among the mean SR of different patches (Table 1). SR (mg $C/m^2/h$) for each patch was in the following order: *Pleurozium* (44 ± 28) > *Cladina* (34 ± 21) > *Aulacomnium* (26 ± 18). SR in winter was negligible small, but was observed (max: 1.0 mg $C/m^2/h$). Because air (–45 - –25 °C) and soil (–18.5 °C) temperature were low extremely, it is considered that CO_2 emission was occurred due to leak from deep layer, not decomposition in winter.

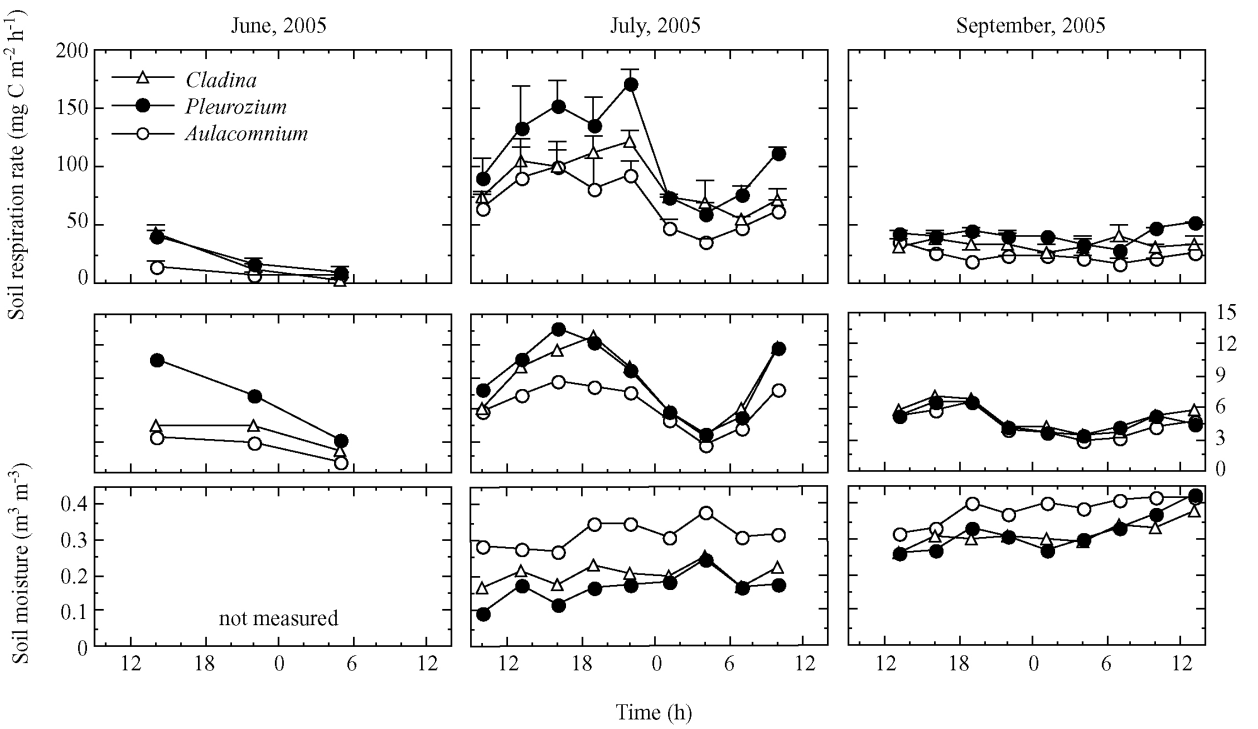

Figure 1. Daily changes in soil respiration, soil temperature, and soil moisture in the *L. gmelinii* forest for the measurement period in June, July, and September 2005. Values are means (+SD).

Relationship between SR and soil temperature and moisture

The relationship between the SR and soil temperature or soil moisture is shown in Figure 2. SR was positively correlated with soil temperature ($r = 0.71$ $P < 0.01$) (Figure 2a) and negatively correlated with soil moisture ($r = –0.57$ $P < 0.01$) (Figure 2b). It is considered that SR in *Aulacomnium* patch was smaller than other patches due to low soil temperature and high soil moisture (Table 1). *Aulacomnium* patches were relatively lower microtpography. So that, rain and melted water could be gathered in the patch and prevented to gas diffusion and to increase soil temperature. The relationship between the SR and soil temperature was somewhat different depending on the month (Figure 2a). SR in June was lower than that in any other months even if the respiration rates were compared at a similar level of soil temperature (Figure 2a). The difference suggests that yearly difference in permafrost thawing would affect the soil respiration: the organic horizon had started to thaw, but the mineral horizon was still frozen in early June. Furthermore, SR includes soil microbial respiration and plant respiration (Raich and Schlesinger 1992). Jiang *et al.* (2005) reported that root respiration was relatively higher in summer than that in spring and autumn, and Q_{10} values of SR and root respiration were different in a larch forest in north-eastern China. So that, the SR in this study might relatively lower in September than that in July due to a decrease in root respiration (Figure 3).

Table 1. Summary of soil temperature, soil moisture, and soil respiration in each patch.

	SR mg C/m^2/h		Temp. ^{o}C		Moist. m^3/m^3	
Cladina	34±21	b	4.3±2.4	a	0.36±0.14	b
Pleurozium	44±28	a	5.0±2.6	a	0.35±0.13	b
Aulacomnium	26±18	c	4.1±2.0	a	0.44±0.14	a

different letters show a significant difference among the vegetation at 5% level

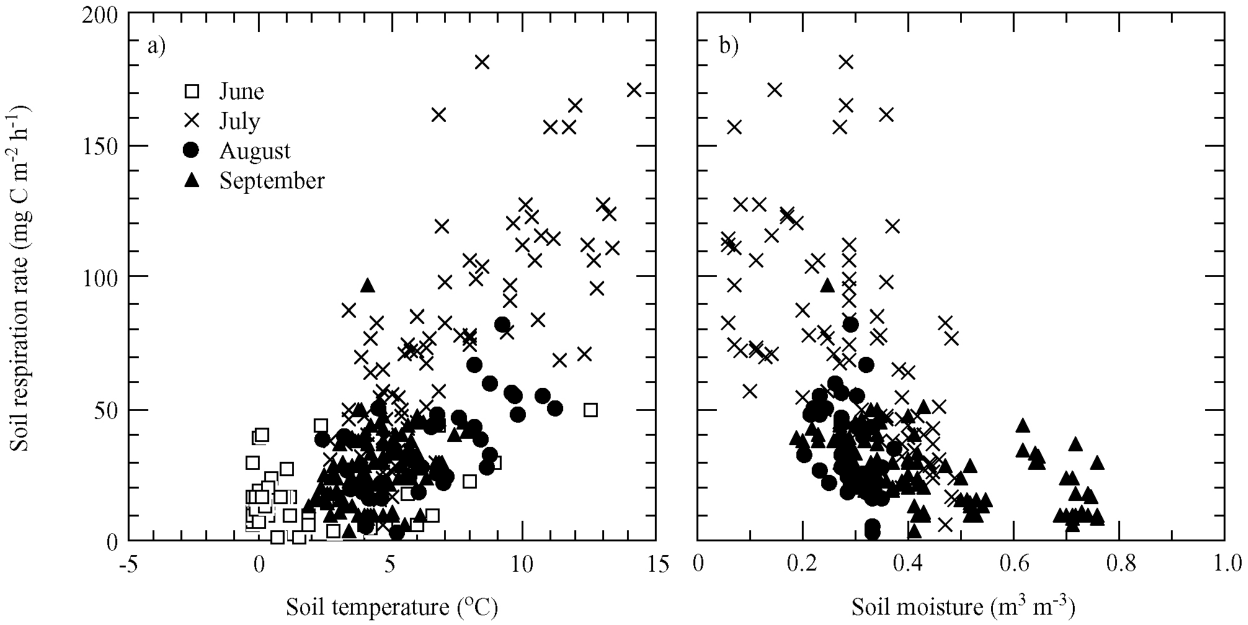

Figure 2. Relationship between soil respiration rate and soil temperature and moisture in the *L. gmelinii* forest.

Annual soil respiration rate

As mentioned in the method, soil was frozen from October to May. So that, growing season was assumed from June to September, and SR in growing season (113 g C/m^2) and winter season (11.9 g C/m^2) was calculated separately from each relationship between SR and soil temperature. The contribution of SR in winter season to annual SR estimated 9.5%. Annual SR of 125 g C/m^2 was smaller than review value of 322 ± 31 g C/m^2 (Raich and Schlesinger 1992). The value in this study was similar to that of 94 ± 16 g C/m^2 in Northern bogs and mires (Raich and Schlesinger 1992). We could not clarify the reason why, but small biomass and peculiar permafrost soil environment in our study site might be related the fact that SR is very low compared with that in other boreal forests.

Conclusion

The soil respiration rate was positively correlated with soil temperature and negatively correlated with soil moisture. The soil respiration rate was the lowest in the *Aulacomnium* patch among the patches examined. This was due to the high soil moisture and low soil temperature. The estimation of annual soil respiration rate was smaller than those previously reported in other permafrost-free boreal forests. Accumulating knowledge of the soil respiration in boreal forests in the regions of the continuous permafrost appears necessary for obtaining better estimates.

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