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Citation	Eurasian Journal of Forest Research, 9(1), 17-28
Issue Date	2006-07
Doc URL	<a href="http://hdl.handle.net/2115/22202">http://hdl.handle.net/2115/22202</a>
Type	bulletin (article)
File Information	9(1)_P17-28.pdf



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## CO<sub>2</sub> Emissions of the Non-tree Vegetation Cover in larch (*Larix gmelinii* (Rupr.) Rupr.) Stands in the Central Evenkia Region of Siberia, Russia

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### Abstract

CO<sub>2</sub> emissions from various vegetation components were studied in larch-dominated stands (*Larix gmelinii* (Rupr.) Rupr.) in the Central Evenkia region of Siberia, Russia, during growing season in 2001. We found a clear relationship between air temperature and CO<sub>2</sub> emission rate of the dominant vegetation components (such as *Sphagnum* and green mosses, lichens, and dwarf shrubs). The CO<sub>2</sub> emission rate of *Sphagnum*, green mosses, and lichens (measured as CO<sub>2</sub> evolution from their surface) ranged from 0.04 to 0.24 mg CO<sub>2</sub> g<sup>-1</sup> oven-dry weight (odw) h<sup>-1</sup> during growing season. The CO<sub>2</sub> emission rate of the aboveground parts of dwarf shrubs ranged from 0.65 to 5.54 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>. The contribution of the different components of the vegetation cover varied among stand types; for example, in *Sphagnum* associations, up to 94% of the total CO<sub>2</sub> emission occurred from the *Sphagnum*–green mosses–lichen cover, whereas in stands dominated by dwarf shrubs, 90% of total CO<sub>2</sub> emission occurs from the dwarf shrubs.

**Key words:** CO<sub>2</sub> emission, Dwarf shrubs, Moss-lichen cover, Siberia, Vegetation cover

### Introduction

Boreal forest ecosystems are one of the main reservoirs of terrestrial organic carbon and are being studied closely by many investigators, especially with respect to the effects of global climate change (Raich and Schlesinger 1992, Wang and Polglase 1995, Apps 2002). In this context, the vegetation cover is of particular interest since it is an important component of the forest ecosystem and plays an essential role in the dynamics and accumulation of nutrients and carbon in boreal forests growing in areas with permafrost (Fukuda 1994; Schulze *et al.* 1997, 1999). Because the carbon dynamics of boreal trees are relatively well understood (Al'tergoth and Hitrovo 1970, Landhausser *et al.* 1996, Mori *et al.* 1998), we have chosen to focus on the vegetation cover, which has not been studied for these ecosystems. The term "vegetation cover" represents both the live vegetation cover (mosses, lichens, and dwarf shrubs) and the litter layer (Melekhov 1980), but does not include the tree layer. The biomass of live vegetation and litter can be quite large in boreal forest ecosystems. Therefore, it is necessary to better understand CO<sub>2</sub> emissions from these vegetated surfaces. Moreover, we must evaluate the effect of various environmental factors, such as temperature and moisture, on the CO<sub>2</sub> emission from the vegetation cover to obtain crucial data on the CO<sub>2</sub> dynamics of this ecosystem component. The objective

of our study was to determine the CO<sub>2</sub> emission rate of individual components of the vegetation cover and their contribution to total CO<sub>2</sub> emissions from the surface as a function of their biomass in several types of larch stands.

### Materials and Methods

#### 1. Description of the study site

The research was carried out from June to September 2001 in fixed experimental plots (EP) established in several types of stand dominated by larch (*Larix gmelinii* (Rupr.) Rupr.) in the Central Evenkia region of Siberia, Russia (64°18'N, 100°11'E) as follows: a dwarf shrub–*Sphagnum* larch stand (EP I-1) situated in the bottom of a valley; a crowberry (*Empetrum nigrum* L.)–bearberry (*Arctostaphylos uva-ursi* L.) larch stand (EP I-2) located on terraces; a cowberry (*Vaccinium vitis-idaea* L.)–green mosses larch stand (EP I-3) in the middle of a northeast-facing slope; a cowberry–blueberry (*Vaccinium uliginosum* L.)–green mosses–lichen larch stand (EP II-2) located on the floodplain of a river; and a *Ledum* (*Ledum palustre* L.)–blueberry–lichen–green mosses larch stand (EP IV-2) in the middle of a west-facing slope.

The characteristics of each plot are given in Table 1. These plots are characterized by differences in the thickness of the vegetation cover and in productivity. Climatic and soil characteristics of the study site were

given by Abaimov *et al.* (1999) and Ershov (1998). Continuous permafrost presenting in this region controls hydrothermal conditions and other environmental factors. According to Prokushkin *et al.* (2005), at the same to ours, studied larch stands permafrost occur at the depth from 0 to 60 cm because of the active layer is deepening during growing season. During the research period from June to September, air

and soil temperatures (daily mean values, Fig. 1) were measured daily on a twenty-four hour basis with auto-logging thermometers (TR 51-A, T&D, Matsumoto, Japan). Air temperatures at breast height during the research period averaged +15.0°C, soil temperature at a depth of 10 cm averaged +7.7°C, and the amount of precipitation from June to September totaled 300 mm.

Table 1. Characteristics of the experimental plots established in the larch stands\*.

EP	Composition	Mean tree diameter (cm)	Mean tree height (m)	Canopy closure (%)	Age (years)	Vegetation cover thickness, including litter (cm)	Stand density (trees ha <sup>-1</sup> )
I-1	100% L.g.**	4.0	4.2	16	72-92	20-25	2670
I-2	90% L.g. & 10% B	6.2	6.1	20	72-92	3-5	770
I-3	100% L.g.	6.6	8.2	57	73-92	8-10	2910
II-2	100% L.g.	7.8	7.4	30	149-260	8-10	2000
IV-2	100% L.g.	9.0	8.0	37	150	15-20	1830

Notes: \* According to Abaimov *et al.* (1997), Prokushkin *et al.* (2002, 2006);

\*\* L.g., *Larix gmelinii* (Rupr.) Rupr.; B, *Betula pendula* Roth.

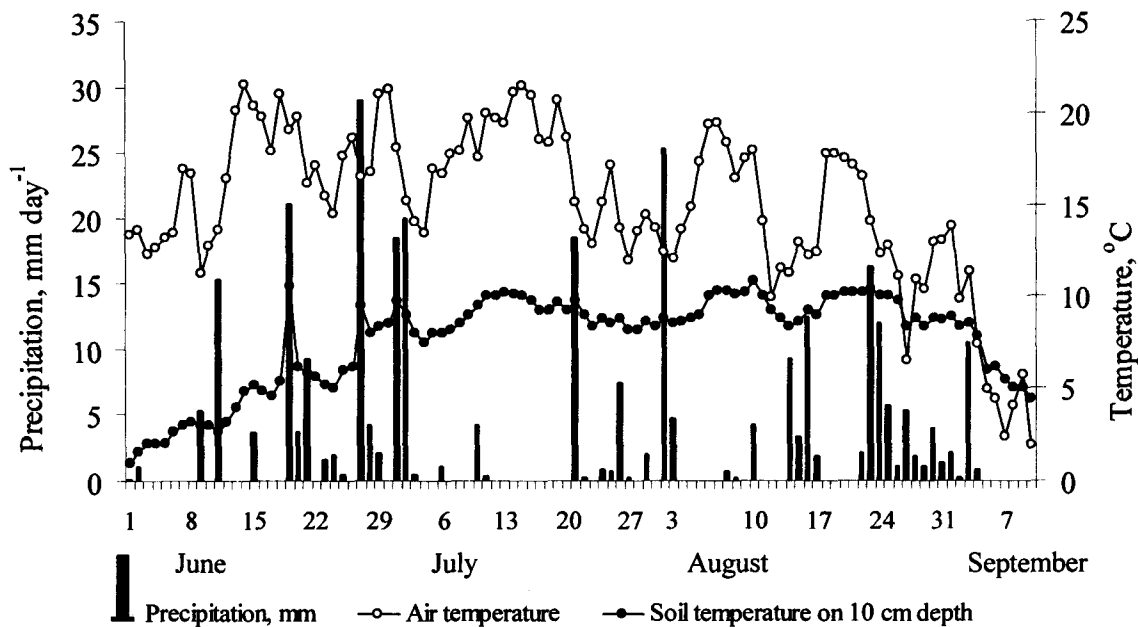


Fig. 1. Mean air and soil temperatures (calculated on the 24 hours basis) and precipitation during the study period.

## 2. Plant materials

We used all components of the vegetation cover, including *Sphagnum* mosses (*Sphagnum fuscum* (Schimp.) Klinggr., *Sphagnum magellanicum* Brid., *Sphagnum wulfianum* Girg.), green mosses (*Aulacomnium turgidum* (Wahlenb.) Schwaegr., *Dicranum polysetum* Sw., *Hylocomium splendens* (Hedw.) B. S. G., *Pleurozium schreberi* (Brid.) Mitt., *Ptilidium ciliare* (L.) Hampe and others), and lichens (*Cetraria islandica* (L.) Ach., *Cladina arbuscula* (Wallr.), *Cladina rangiferina* (L.) Web., *Cladina stellaris* (Opiz) Brodo, *Peltigera aphthosa* (L.) Willd. and others), including both the litter layer and the roots of dwarf shrubs, and the aboveground parts of the dwarf shrubs (*Vaccinium vitis-idaea*, *Vaccinium uliginosum*, *Ledum palustre*, *Empetrum nigrum*, *Arctostaphylos uva-ursi*) for the CO<sub>2</sub> emission measurements. These were the dominant plants in the studied stands based on projected cover and biomass. We did not differentiate between different communities of *Sphagnum*, green mosses, and lichens based on their species composition.

Using method of Ponyatovskaya (1964) for biomass assessment, each of the component biomass was determined for use in the calculation of the CO<sub>2</sub> emissions using 20 × 25 cm plots equal in depth to the depth of the living vegetation with 7 to 10 replications in each stand type, but not in the same place of CO<sub>2</sub> emissions measurement, it was separated by a significant distance (about 10 m) and the experimental plot size for each stand was 20 × 20 m in each stand type, so it could not affect environmental conditions. To estimate biomass, we destructively sampled all the vegetation inside each 20 × 25 cm plot (*Sphagnum*, green mosses, and lichens, plus the litter and dwarf shrub roots to the permafrost level, and the aboveground parts of dwarf shrubs) and sorted it by *Sphagnum*, green moss, lichen and dwarf shrub groups. We oven-dried all plant materials to obtain the

oven-dried weight (odw) at 104°C and calculated the total stocks (t ha<sup>-1</sup>) in each plot. Information about the composition, projected area, and biomass of each component of the vegetation cover is given in Table 2.

## 3. CO<sub>2</sub> emission measurements

We measured CO<sub>2</sub> emission rates of the non-shrub components of the vegetation cover *in situ* using an infrared gas analyzer (IRGA; Li-6200, LiCor, Lincoln, NE, USA) equipped with a soil (dark) respiration chamber (model 6000-09), which excludes the effects of CO<sub>2</sub> assimilation by plants inside the chamber. The chamber volume was 962 cm<sup>3</sup>, and it covered a soil surface area of 78.5 cm<sup>2</sup>. The flow rate was set to between 0.1 and 2 L min<sup>-1</sup>, with the rate adjusted manually to produce steady-state conditions within the chamber. The respiration chambers were inserted to a depth of 10 cm in the soil in plots with *Sphagnum*–green mosses–lichen cover, thus the measurements also included CO<sub>2</sub> emissions of litter, any root, and soil in these samples. When we measured respiration by dwarf shrubs, we used specially designed plastic rings inserted to a depth of 10 cm in the soil. The height of the plastic rings (from 10 to 25 cm) were changed according to the height of the dwarf shrubs and the chamber volume for the calculation of the CO<sub>2</sub> emission rate was changed according to the height of the rings. In addition, we isolated the aboveground parts of the shrubs in the chamber from the underlying *Sphagnum*, green mosses, and lichen using clay and plastic film insulating materials to exclude CO<sub>2</sub> flux through the ground surface; thus, we only recorded respiration rates for the aboveground parts of the dwarf shrubs. The measurement of root respiration of dwarf shrubs was included in measurements of mosses and lichens associated with litter and any roots.

We studied the relationship between temperature and CO<sub>2</sub> emissions for every component of the vegetation cover from June to September by controlling the air

Table 2. Projected cover (%) and biomass (t ha<sup>-1</sup>) of the vegetation cover in the studied larch stands.

EP	<i>Sphagnum</i> with litter and roots	Green mosses with litter and roots	Lichens with litter and roots	Dwarf shrubs (aboveground parts)***	Total biomass
I-1	20* 81.39**	26 4.48	32 8.08	27 0.69	94.64
I-2	-	-	8 9.12	33 3.6	12.72
I-3	-	55 57.72	6 10.95	14 2.07	70.74
II-2	-	47 19.99	34 14.48	17 2.12	36.59
IV-2	-	85 39.42	30 25.84	52 0.81	66.07

Notes: EP experimental plot.

\* Projected cover (%). \*\* Biomass (t ha<sup>-1</sup>).

\*\*\* Sum for all dwarf shrubs. – not observed in the plot.

temperature inside the chamber and recording CO<sub>2</sub> emission at temperatures from +5 to +40°C at 5°C intervals. Air temperatures inside the chamber were checked using the display of the IRGA to within 0.5°C. To cool the air inside the chamber, we used ice packs; to heat the air, we used hot water containers. The air temperature inside the respiration chamber was obtained using the thermometer mounted inside the chamber. Before every CO<sub>2</sub> emission measurement at each temperature, we left the chamber for about 40 min until its temperature had stabilized. CO<sub>2</sub> emission rates for the vegetation cover components were calculated on the basis of oven-dry weight. For that, we performed destructive sampling of *Sphagnum* moss, green mosses, lichens and dwarf shrubs after each measurement. Then, we removed mineral soil and separated the measured materials into live and dead parts (including litter and roots), then oven-dried the materials at 104°C to obtain the oven-dried weights (odw). In this connection, we created new CO<sub>2</sub> emission measurement plots after each measurement of CO<sub>2</sub> emissions and destructive sampling of the biomass.

In the Central Evenkia region, the water content of the components of the dominant vegetation cover, excluding dwarf shrubs, ranged from 35% to 96% in different stands, varied in a narrow range for a given experimental plot (stand type) during the measurement period, and had no significant effect on the measured CO<sub>2</sub> emissions. Therefore, in the remainder of our analysis, we only accounted for temperature effects on the respiration rate when we calculated CO<sub>2</sub> emissions from the surface of the vegetation cover.

#### 4. Calculation of temperature coefficient values and CO<sub>2</sub> emissions

Temperature coefficient ( $Q_{10}$ ) values are typically calculated using the following equation:

$$Q_{10} = \frac{R^{T+10^{\circ}\text{C}}}{R^T} \quad [1],$$

where  $Q_{10}$  is the temperature coefficient for the CO<sub>2</sub> emission rate;  $R^T$  is the CO<sub>2</sub> emission rate (mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>) at a given temperature  $T$  (°C); and  $R^{T+10^{\circ}\text{C}}$  is the CO<sub>2</sub> emission rate at a temperature 10°C greater than  $T$ . In this study, we set  $T$  equal to the daily mean air temperature, following the method of Semikhatova (1995) that says that in the context of Adaptation Theory, it is more correct to compare plant characteristics of different habitats at typical environmental conditions.

The amount of CO<sub>2</sub> emitted by each component of the vegetation cover (*Sphagnum* with litter and roots; green mosses with litter and roots; lichens with litter and roots; aboveground parts of dwarf shrubs) was calculated per unit of biomass ( $B^{comp}$ ) using equation [2]:

$$F^{comp} = \sum R^{comp}_{day} \times B^{comp} \times 24 \times 10^{-6} \quad [2],$$

where  $F^{comp}$  is the daily total rate of CO<sub>2</sub> emission (kg ha<sup>-1</sup> day<sup>-1</sup>);  $R^{comp}_{day}$  is the daily mean CO<sub>2</sub> emission rate of each component of the vegetation cover (mg CO<sub>2</sub> g<sup>-1</sup>

odw h<sup>-1</sup>);  $B^{comp}$  is the biomass of live *Sphagnum*, green mosses, and lichen, including litter and roots or of the aboveground part of dwarf shrubs (g ha<sup>-1</sup>); 24 is the number of hours in a day; and 10<sup>-6</sup> is the conversion factor between mg and kg of CO<sub>2</sub>.

We used STATISTICA v.6.0 (StatSoft, Tulsa, USA) for all statistical analyses.

## Results and Discussion

### 1. Relationships between temperature and CO<sub>2</sub> emission rate

In boreal forests, temperature is typically the main factor that limits biological processes, including ecosystem respiration; thus, respiration rate depends most closely on temperature (Amthor 1994). Our results confirmed that vegetation moisture content had no effect on CO<sub>2</sub> emission, and thus, that temperature was the dominant factor. During the vegetative period, increasing temperature from +5°C to +35°C increased CO<sub>2</sub> emissions by *Sphagnum*, green mosses, lichens, and dwarf shrubs from 0.02 to 0.49, 0.02 to 0.60, 0.02 to 0.37, and 0.14 to 12.58 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>, respectively (Fig. 2). The temperature response of CO<sub>2</sub> emission followed the equations shown in Table 3. Aboveground respiration by *V. vitis-idaea* increased from 0.18 to 5.55 in June, from 1.22 to 12.58 in July, from 0.53 to 3.86 in August, from 2.56 to 7.15 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup> in September as temperatures increased from +5°C to +35°C (Fig.2). A narrower range of variation in this species in Alaskan tundra was reported by Limbach *et al.* (1982); as temperatures increased from +5°C to +30°C, CO<sub>2</sub> emission rate increased from 0.63 to 0.97 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>.

The CO<sub>2</sub> emission rate of all vegetation components increased exponentially as air temperature increased. However, in some cases the respiration rate of dwarf shrubs was higher at +5°C than at +10°C. The same phenomenon has been reported in previous studies, most of which associated this effect with the changes in the physical properties of water in plant tissues at temperatures between -3 and +5°C (Al'tergoth and Hitrovo 1970, Miroslavov 1994, Landhausser *et al.* 1996).

During the vegetative period, we observed two significant maxima for the CO<sub>2</sub> emission rate of dwarf shrubs: one in July and another in the first ten days of September (Fig. 3, Table 4). The results of previous studies (Evdokimova 1985, Luk'yanova *et al.* 1986, Shuvalova 1988) suggest that the July maximum occurs during the active period of development of generative organs (i.e., the bud-formation phase) and of flowering, and the second occurs during preparation for the plant's quiescent period or in response to stress imposed by early frosts. The latter hypothesis is reasonable because temperatures in the Central Evenkia region usually reached 0°C by late August. At the end of the vegetative period, when the daily mean air temperature was near 0°C and night frosts occurred, the CO<sub>2</sub> emission rates of *Sphagnum*, green mosses, and lichens all increased (Fig. 2). This may have resulted from the fact that soil temperature became higher than air temperature during September due to thermal lag of a

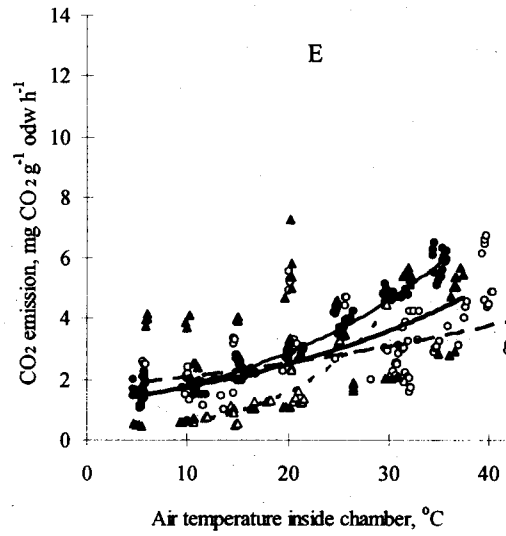
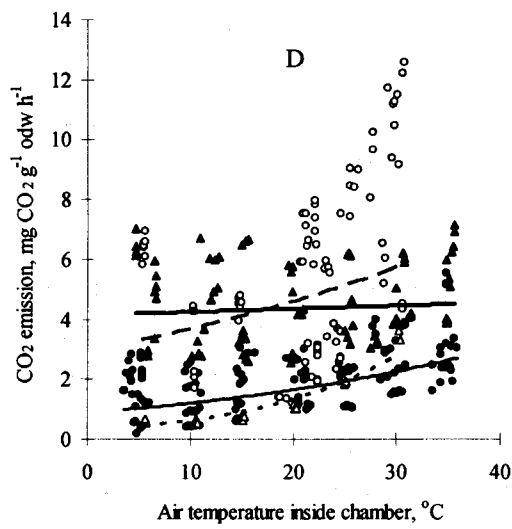
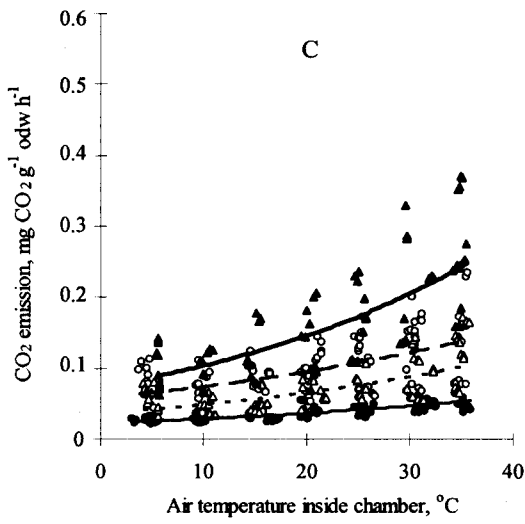
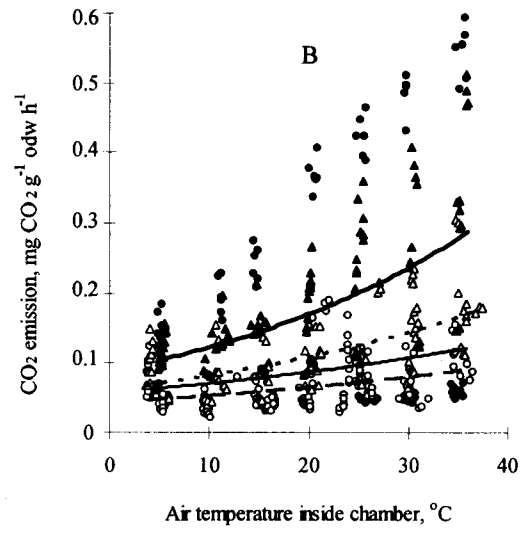
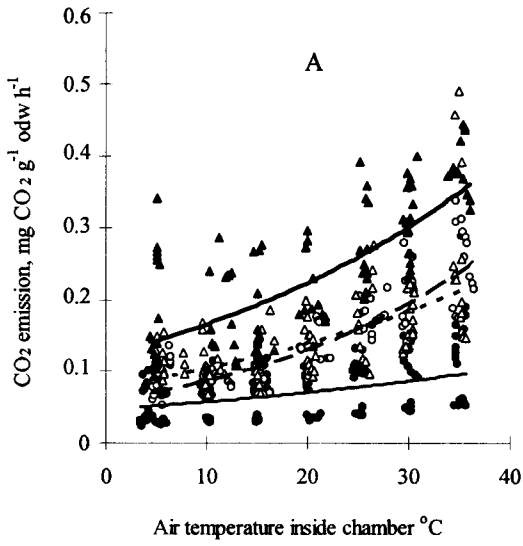
soil (Fig. 1). When the soil temperature was higher than the air temperature, thermal inversion can accelerate CO<sub>2</sub> diffusion in the air-filled pores in the vegetation surface and thus cause large CO<sub>2</sub> emissions from the *Sphagnum*–green mosses–lichen cover (Ivannikova and

Semenova 1988, Gryaz'kin and Tarasov 1989). In other words, environmental conditions at the end of growing period became more favorable for CO<sub>2</sub> emission into the atmosphere.

Table 3. Equations\* describing the relationship between air temperature and CO<sub>2</sub> emission for the vegetation components of the larch stands in the study.

Vegetation component	Month	a	b	r <sup>2</sup>	p
<i>Sphagnum</i> with litter and roots	June	0.0468	0.0206	0.22	0.000
	July	0.0581	0.0404	0.74	0.000
	August	0.0788	0.0284	0.4	0.000
	September	0.1238	0.0297	0.53	0.000
Green mosses with litter and roots	June	0.0574	0.0211	0.09	0.001
	July	0.0433	0.0206	0.1	0.000
	August	0.0619	0.0283	0.4	0.000
	September	0.0881	0.033	0.45	0.000
Lichens with litter and roots	June	0.0222	0.0247	0.58	0.000
	July	0.0575	0.025	0.37	0.000
	August	0.0361	0.0297	0.46	0.000
	September	0.0735	0.0342	0.56	0.000
<i>V. vitis-idaea</i> (aboveground parts)	June	0.8784	0.0314	0.25	0.000
	July	2.9475	0.0222	0.12	0.001
	August	0.2946	0.0749	0.77	0.000
	September	4.137	0.0025	0.003	0.651
<i>V. uliginosum</i> (aboveground parts)	June	1.1192	0.0472	0.92	0.000
	July	1.7078	0.0198	0.21	0.000
	August	0.1965	0.1035	0.79	0.000
	September	1.2114	0.0363	0.26	0.000
<i>L. palustre</i> (aboveground parts)	June	0.4657	0.044	0.58	0.000
	July	1.6942	0.019	0.06	0.002
	August	0.4942	0.0471	0.46	0.000
	September	1.5388	0.024	0.19	0.000
<i>E. nigrum</i> (aboveground parts)	June	0.1554	0.0598	0.72	0.000
	July	0.4944	0.0398	0.4	0.000
	August	0.5897	0.0295	0.34	0.000
	September	1.4584	0.015	0.23	0.000
<i>A. uva-ursi</i> (aboveground parts)	June	0.6903	0.0279	0.69	0.000
	July	0.2777	0.0464	0.32	0.000
	August	0.8796	0.0068	0.002	0.680
	September	1.9766	0.0155	0.24	0.000

Notes: \* Equation has a form  $R_{day}^{comp} = a e^{bT}$ . In the equations,  $R_{day}^{comp}$  is the daily mean CO<sub>2</sub> emission rate of the vegetation component (mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>) and  $T$  is the mean daily air temperature (°C).



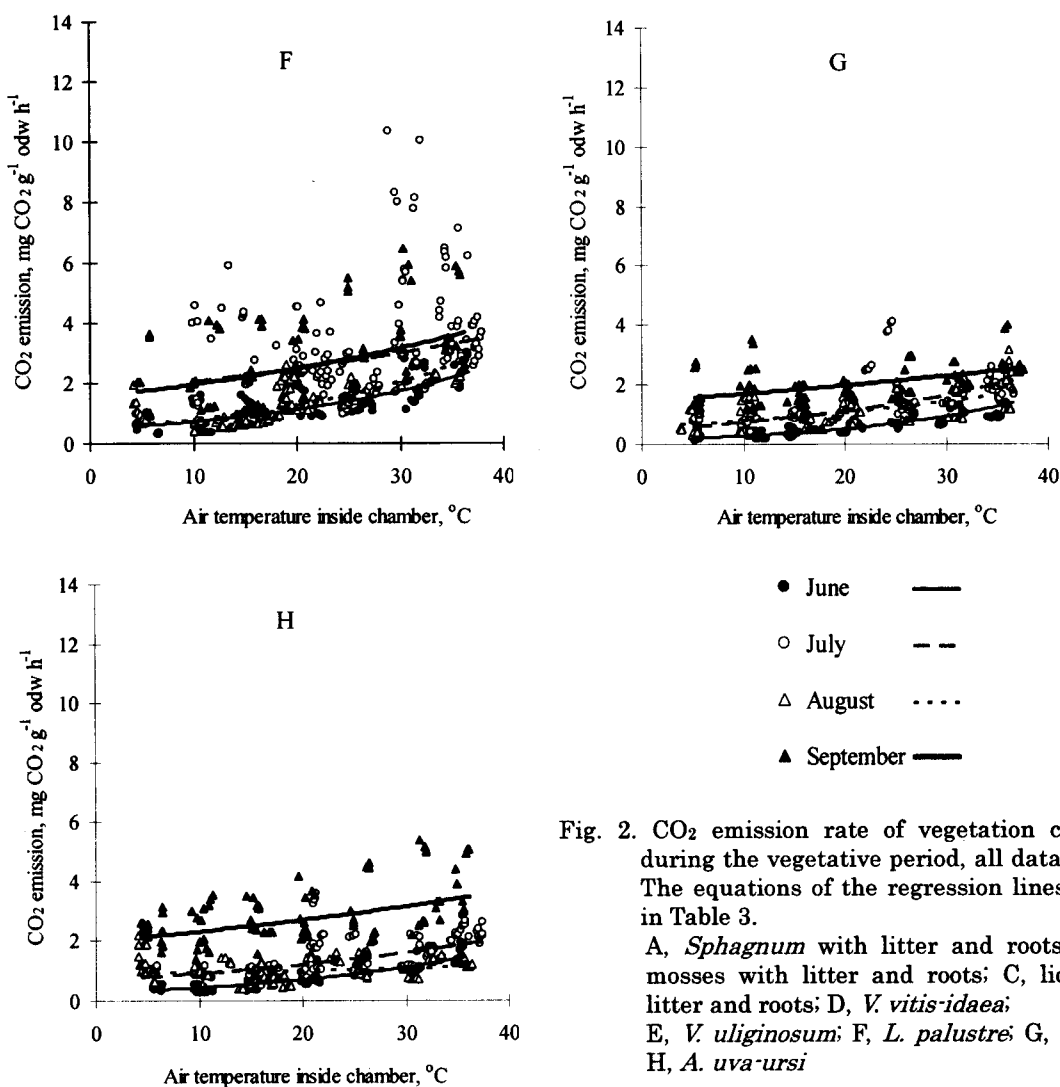


Fig. 2. CO<sub>2</sub> emission rate of vegetation components during the vegetative period, all data combined. The equations of the regression lines are given in Table 3.

A, *Sphagnum* with litter and roots; B, green mosses with litter and roots; C, lichens with litter and roots; D, *V. vitis-idaea*; E, *V. uliginosum*; F, *L. palustre*; G, *E. nigrum*; H, *A. uva-ursi*

Table 4. Mean values of CO<sub>2</sub> emission rate (mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>\*) of vegetation cover components during the vegetative period.

Vegetation cover component	June	July	August	September
Green mosses with roots and litter	0.146±0.014	0.074±0.004	0.123±0.006	0.189±0.011
<i>Sphagnum</i> with roots and litter	0.078±0.003	0.149±0.007	0.155±0.008	0.241±0.010
Lichens with roots and litter	0.037±0.001	0.105±0.005	0.074±0.004	0.164±0.009
Aboveground dwarf shrubs	1.61±0.05	2.81±0.09	1.25±0.03	3.08±0.07
<i>L. palustre</i>	1.37±0.06	3.19±0.14	1.33±0.06	2.86±0.16
<i>V. vitis-idaea</i>	1.88±0.08	5.54±0.32	1.43±0.26	4.56±0.15
<i>V. uliginosum</i>	3.17±0.13	3.19±0.14	1.52±0.16	3.10±0.20
<i>A. uva-ursi</i>	0.85±0.04	1.45±0.06	1.10±0.04	2.84±0.10
<i>E. nigrum</i>	0.65±0.04	1.40±0.07	1.20±0.06	2.06±0.07

Notes: \* The monthly average CO<sub>2</sub> emission rate was calculated from the air temperature and the temperature-CO<sub>2</sub> emission rate relationships (Table 3)



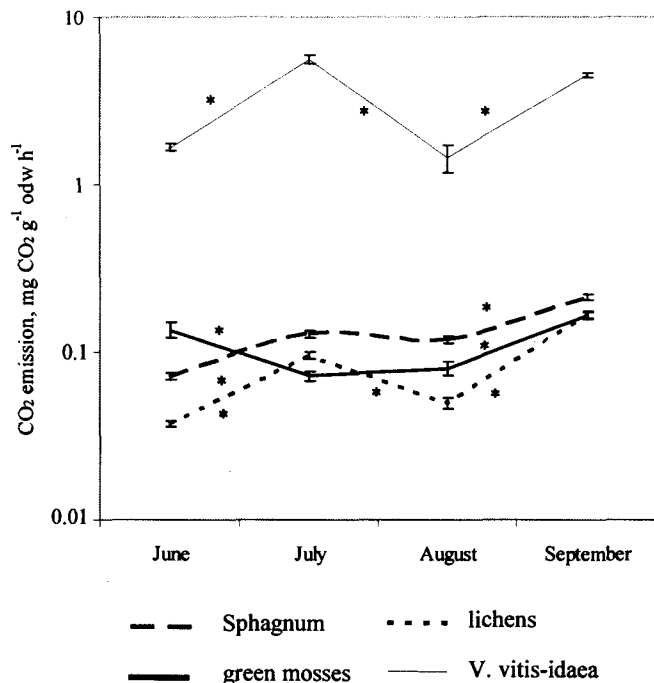


Fig. 3. Monthly mean CO<sub>2</sub> emission of vegetation in growing season \* indicate significant change in emission rate at  $p < 0.05$  (Tukey HSD test,  $MS=0.0029$ ,  $df=294$ ).

Table 5.  $Q_{10}$  of vegetation cover components during the vegetative period.

Vegetation cover component	Air temperature range	June	July	August	September
Green mosses with roots and litter	5-15°C	1.25	0.96	1.04	1.23
	15-25°C	1.61	1.41	1.41	1.60
	25-35°C	1.28	1.29	1.50	1.45
<i>Sphagnum</i> with roots and litter	5-15°C	1.10	1.13	0.94	0.92
	15-25°C	1.24	1.88	1.53	1.68
	25-35°C	1.42	1.47	1.61	1.37
Lichens with roots and litter	5-15°C	1.13	0.99	1.03	1.12
	15-25°C	1.49	1.52	1.49	1.45
	25-35°C	1.24	1.31	1.45	1.55
<i>L. palustre</i> *	5-15°C	1.46	-	0.91	1.14
	15-25°C	1.39	0.63	1.90	1.40
	25-35°C	1.88	1.98	1.07	1.07
<i>V. vitis-idaea</i> *	5-15°C	1.02	0.70	1.19	0.84
	15-25°C	1.42	1.36	2.66	0.99
	25-35°C	1.40	-	-	1.31
<i>V. uliginosum</i> *	5-15°C	1.50	0.93	-	1.15
	15-25°C	1.71	1.58	3.42	1.21
	25-35°C	1.49	0.99	-	1.52
<i>A. uva-ursi</i> *	5-15°C	1.20	0.85	0.54	1.13
	15-25°C	1.92	1.52	1.62	1.04
	25-35°C	1.52	1.56	1.05	1.42
<i>E. nigrum</i> *	5-15°C	1.67	1.35	1.00	0.95
	15-25°C	1.85	2.04	1.57	1.28
	25-35°C	1.81	1.07	1.49	1.43

Notes: \* Only includes data for EP I-1, EP I-2, and EP I-3.  
- insufficient temperature data.

Temperature responses of respiration (or CO<sub>2</sub> emission) can be evaluated using the  $Q_{10}$  temperature coefficient, which represents the increase in respiration rate for a 10°C increase in temperature.  $Q_{10}$  values for CO<sub>2</sub> emission of *Sphagnum*, green mosses, lichens, and dwarf shrubs ranged from 0.92 to 1.88, 0.96 to 1.61, 0.99 to 1.55, and 0.54 to 3.42, respectively, during the vegetative period (the average values presented are the minimum and maximum for all months combined, Table 5). The fact that  $Q_{10}$  was  $< 1.88$  for *Sphagnum*, green mosses, and lichens (Table 5) indicates a dominant effect of temperature on physical processes (e.g., diffusion of CO<sub>2</sub>) rather than biological processes (root and microbial respiration) during the vegetative period (Semikhatova 1968). In contrast, the higher  $Q_{10}$  values of dwarf shrubs (up to 3.42) during growing period were caused by biological processes (plant respiration) depending on temperature (Table 5). Some studies have reported very high values (3.0) for  $Q_{10}$  of plants at low air temperatures (+5 to +10°C), but only for species that are not psychrotolerant during the period of adaptation to low temperatures (Yokota and Hagihara 1996). Under the permafrost conditions of the Central Evenkia region (Table 5), we have not observed such a large increase of  $Q_{10}$  in dwarf shrubs that can adapt to northern areas at low temperatures (+5 to +15°C). We found that the average (June to September)  $Q_{10}$  value for the deciduous dwarf shrub *V. uliginosum* (= 1.55, maximum  $Q_{10} = 3.42$ ) was greater than that of evergreen dwarf shrubs (*V. vitis-idaea*, *L. palustre*, *E. nigrum*, *A. uva-ursi*), which ranged from 1.29 to 1.38 (Table 5). In other words, deciduous dwarf shrubs are more sensitive to temperature changes than evergreen ones and incur supplemental energy costs to permit normal functioning under the severe taiga conditions in the Central Evenkia region (Limbach et al. 1982). Overall, respiration rate of the aboveground parts of the dwarf shrubs was ten times that of the *Sphagnum*, green mosses, and lichens, including litter and roots.

## 2. CO<sub>2</sub> emission by the vegetation cover in larch-dominated stands

Our studies showed that the CO<sub>2</sub> emission rate of green mosses (with litter and roots) differed little from that of *Sphagnum* (with litter and roots): 0.074 to 0.189 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup> versus 0.078 to 0.241 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>, respectively (Table 4). The total daily CO<sub>2</sub> emission (Table 6) from each component of the vegetation cover in each larch stand was calculated using equation [2] on the basis of the relationships between air temperature and CO<sub>2</sub> emission (Table 3) for each month and the biomass of each component in each stand type (Table 2). The total CO<sub>2</sub> emission rate was calculated using the daily mean air temperature. For the green mosses (with litter and roots), CO<sub>2</sub> emissions during the vegetative period averaged from 6.59 to 152.86 kg ha<sup>-1</sup> day<sup>-1</sup> (Table 6), depending on the stand type. For the *Sphagnum* (with litter and roots) in dwarf shrub-*Sphagnum* larch stands (EP I-1), CO<sub>2</sub> emissions during the vegetative period averaged from 129.29 to 295.94 kg ha<sup>-1</sup> day<sup>-1</sup> (Table 6). Thus, despite their low CO<sub>2</sub> emission rate, the large stocks of green

mosses and *Sphagnum* make these vegetation components important sources of atmospheric CO<sub>2</sub>, like in EP I-1. Their contribution to the CO<sub>2</sub> emission amounts to 2% to 86% of the total emission by the vegetation cover, depending on the type of larch stand (Fig. 4).

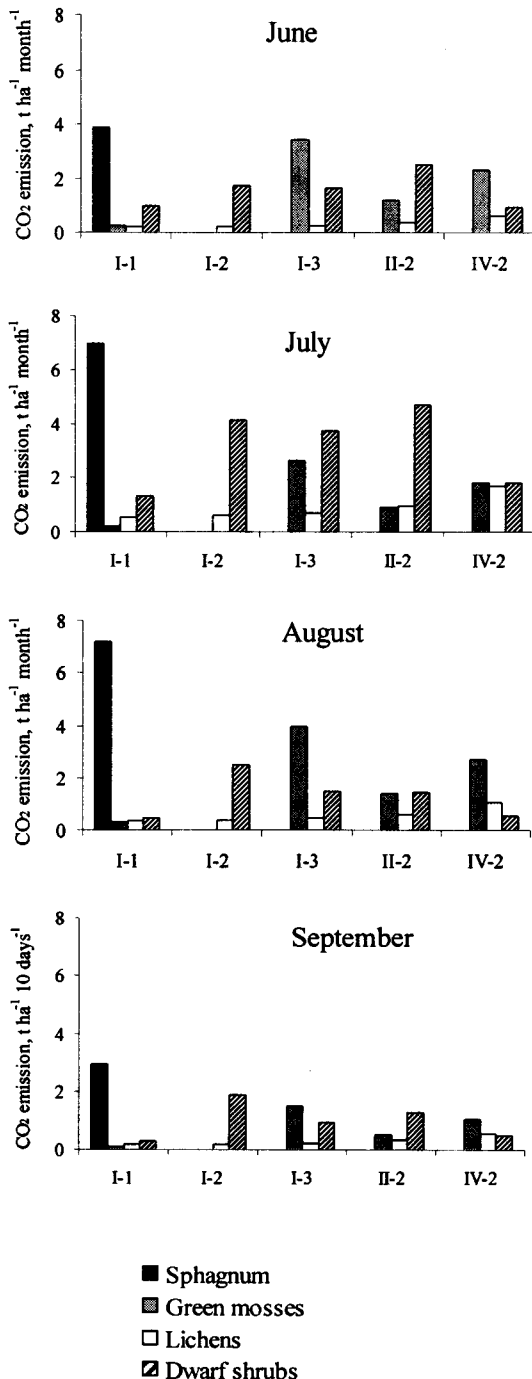


Fig. 4. CO<sub>2</sub> emission by *Sphagnum*, green mosses, lichens, and dwarf shrubs in the studied larch stands during the 2001 vegetative period. For the first three vegetation components, CO<sub>2</sub> emission includes that of the litter and roots underlying this vegetation; for the dwarf shrubs, only the aboveground components are included.

Our findings for Central Evenkia are supported by previously published data. For example, Inoue *et al.* (1995) evaluated CO<sub>2</sub> emission by the vegetation cover in peat wetlands in western Siberia and reported a rate of 108.8 mg C m<sup>-2</sup> h<sup>-1</sup> (equivalent to 96.6 kg CO<sub>2</sub> ha<sup>-1</sup> day<sup>-1</sup>). Blodau and Moore (2003) estimated CO<sub>2</sub> emissions in Canadian peat wetlands to be between 6.1 and 140 mmol CO<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> (equivalent to 2.7 to 62.0 kg ha<sup>-1</sup> day<sup>-1</sup>), and Bubier *et al.* (2003) reported values of 2.1 to 6.1 μmol CO<sub>2</sub> m<sup>-2</sup> sec<sup>-1</sup> (equivalent to 79.8 to 231.9 kg ha<sup>-1</sup> day<sup>-1</sup>) for peat wetlands near Lake Ontario. Silvola *et al.* (1996) studied CO<sub>2</sub> emissions by tundra (Finland) and reported values of about 60 to 200 g C m<sup>-2</sup> per year (equivalent to 6.1 to 20.3 kg CO<sub>2</sub> ha<sup>-1</sup> day<sup>-1</sup>).

The CO<sub>2</sub> emission rate of lichens (with litter and roots) averaged from 0.037 to 0.164 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup> (Table 4). This is close to previously reported respiration rates for lichens; for example, Nash (1996) reported values of from 0 to 5 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup> (Arctic). Based on the biomass of lichens with roots and litter (Table 2), total daily CO<sub>2</sub> emissions during the vegetative period averaged from 6.53 to 57.58 kg ha<sup>-1</sup> day<sup>-1</sup> (Table 6); that is, their contribution to total CO<sub>2</sub> emission by the vegetation cover amounted to 4% to 32%, depending on the stand type (Fig. 4). On the whole, CO<sub>2</sub> emission by the *Sphagnum*, green mosses, and lichen components of the vegetation cover amounted to between 10% and 94% of the total CO<sub>2</sub> emissions, including dwarf shrubs (Fig. 4).

The CO<sub>2</sub> emission rate of the dwarf shrubs (aboveground parts) averaged from 0.65 to 5.54 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup> during the vegetative period (Table 4). Larher (1981) found similar respiration rates by dwarf shrubs (from 0.2 to 16.5 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup>) in mountain areas of the Tyrolean Alps, and Gerasimenko *et al.* (1996) reported a mean value of ca. 5.6 mg CO<sub>2</sub> g<sup>-1</sup> odw h<sup>-1</sup> for dwarf shrubs on Russia's Vrangeli Island. Based on their biomass in the larch stands (Table 2), total daily CO<sub>2</sub> emission from the aboveground parts of the dwarf shrubs during the vegetative period ranged from 0.22 to 99.70 kg ha<sup>-1</sup> day<sup>-1</sup> (Table 6), depending on the stand type. The CO<sub>2</sub> emission rate of the dwarf shrubs thus seems to be an important component of total CO<sub>2</sub> evolution by the vegetation cover (for example, in EP I-2), and amounts to 6% to 90% of the total (Fig. 3) depending on the stand type. The maximum contribution was by *L. palustre* and the minimum was by *E. nigrum* and *V. uliginosum*.

CO<sub>2</sub> emission by the vegetation cover reached its maximum in July (Fig. 4), during the period of active growth with favorable weather, and this increase is likely to be related to rising metabolic costs for growth and development of plant tissues at that time. Among the studied larch stands, the dwarf shrub-*Sphagnum* larch stand (EP I-1) produced the maximum CO<sub>2</sub> emission from the vegetation cover (Fig. 4). This results from the dominance and large biomass of *Sphagnum* in this stand type (Table 2). Despite the low CO<sub>2</sub> emission rate of *Sphagnum* (Fig. 2A), the large biomass made this genus responsible for a large amount of CO<sub>2</sub> emitted from the surface in this stand (Fig. 4).

Table 6. Total daily emission of CO<sub>2</sub> by the vegetation components (kg ha<sup>-1</sup> day<sup>-1</sup>\*) in the studied larch stands during 4 months of the vegetative season in 2001.

Vegetation cover component	June	July	August	September
Green mosses with roots and litter	from 8.80±0.10 to 113.42±1.33	from 6.59±0.07 to 84.90±0.89	from 10.01±0.16 to 128.92±2.07	from 11.87±0.48 to 152.86±6.17
<i>Sphagnum</i> with roots and litter	129.29±1.48	225.04±4.63	231.75±3.74	295.94±10.72
Lichens with roots and litter	from 6.53±0.09 to 20.87±0.29	from 17.01±0.22 to 54.38±0.69	from 10.74±0.18 to 34.35±0.58	from 18.00±0.75 to 57.58±2.41
Aboveground parts of dwarf shrubs	from 32.17±0.75 to 84.20±1.95	from 42.02±0.43 to 152.73±1.62	from 15.28±0.74 to 80.27±1.26	from 30.59±1.00 to 188.03±2.84
<i>L. palustre</i> **	from 4.00±0.10 to 41.92±1.02	from 9.52±0.09 to 99.70±0.97	from 3.99±0.11 to 41.80±1.11	from 7.38±0.21 to 77.31±2.25
<i>V. vitis-idaea</i> **	from 2.15±0.04 to 16.83±0.29	from 6.17±0.07 to 48.35±0.55	from 1.27±0.05 to 9.95±0.42	from 6.07±0.02 to 47.44±0.14
<i>V. uliginosum</i> **	from 0.60±0.02 to 27.50±0.72	from 0.57±0.01 to 26.33±0.27	from 0.22±0.01 to 10.01±0.58	from 0.37±0.02 to 17.15±0.76
<i>A. uva-ursi</i> **	19.31±0.50	35.04±0.50	30.71±0.12	69.47±1.29
<i>E. nigrum</i> **	from 0.41±0.01 to 16.19±0.54	from 0.93±0.02 to 36.56±0.74	from 0.87±0.01 to 33.99±0.57	from 1.55±0.03 to 60.76±1.09

Notes: \* Emission rate was calculated based on the biomass in Table 2;

\*\* Only includes data for EP I-1, EP I-2, and EP I-3.

In this stand type, CO<sub>2</sub> emission from the remaining vegetation cover components was less than 30% of the total emission.

Our results suggest that dwarf shrubs (aboveground parts) and mosses (with litter and roots) are both important components of total CO<sub>2</sub> emission by the vegetation cover, especially in July, when they grow most actively. Dwarf shrub biomass in stand types EP I-1, EP I-2, EP I-3, EP II-1, and EP IV-2 amounted to 0.7%, 28%, 2.9%, 5.8%, and 1.2% of the total vegetation cover biomass, respectively. However, CO<sub>2</sub> emission by dwarf shrubs per unit area was higher than that of lichens (with litter and roots) in all plots except EP IV-2 during the vegetative period.

The proportion of total CO<sub>2</sub> emission by mosses and lichens (with litter and roots) varied little during the vegetative period. This probably resulted from the stable weather during the study period (Fig. 1). Precipitation occurred throughout the vegetative period (June, 99 mm; July, 99 mm; August, 87 mm; and the first 10 days of September, 15 mm) and did not appear to affect the physical properties of the vegetation cover and litter and did not influence CO<sub>2</sub> emission by the vegetation cover. Similarly, there was little influence of air temperature on the vegetation cover components during the vegetative period. Average monthly air temperature remained stable during the growing period

(June, +16.7°C; July, +16.8°C; August, +14.3°C), though the first 10 days of September were noticeably cooler (+6.6°C). Because of these factors, the proportion of total CO<sub>2</sub> emission accounted for by *Sphagnum*, green mosses, and lichens (with roots and litter) was also stable during the vegetative period, especially in larch stands with high biomass in the vegetation cover (e.g., EP I-1, EP I-3, and EP IV-2). The contribution of these vegetation components to total CO<sub>2</sub> emission in these stand types ranged up to 20%, depending on the temperature. Only in July did this contribution decrease, and this seems to have resulted from increased respiration by dwarf shrubs (Fig. 4).

### Conclusions

In this study, we determined the relationship between temperature and CO<sub>2</sub> emission by dwarf shrubs, *Sphagnum*, green mosses, and lichen cover during the vegetative period, and we assessed seasonal CO<sub>2</sub> emission from the vegetation cover based on these relationships. Seasonal changes in CO<sub>2</sub> emission rate of *Sphagnum*, green mosses, and lichens (with litter and roots) were not clearly defined, whereas dwarf shrubs showed obvious seasonal changes. We observed two significant peaks in the respiration rate of dwarf shrubs: one in July and another in September, with a minimum

in August. Total daily CO<sub>2</sub> production by the vegetation cover in larch stands varied among seasons and stand types. The contribution of dwarf shrubs to CO<sub>2</sub> emission increased in the middle of the summer (July), probably as a result of increased respiration costs for growth and metabolism. Correspondingly, the contribution of CO<sub>2</sub> emission by *Sphagnum*, green mosses, and lichens decreased at that time. Among the dwarf shrubs, *L. palustre* had the largest contribution to total CO<sub>2</sub> emission, and the minimum contribution was by *E. nigrum* and *V. uliginosum*. The overall contribution of dwarf shrub CO<sub>2</sub> emission to CO<sub>2</sub> emission by the vegetation cover ranged from 6% to 90%, depending on the stand type. CO<sub>2</sub> emission by the mosses and lichens accounted for a considerable part of total CO<sub>2</sub> emission by the vegetation cover, especially in *Sphagnum* associations, and varied between 10% and 94%, depending on the stand type. This contribution related to the considerable biomass in the live components of the vegetation cover and in the underlying roots and litter.

#### Acknowledgments

This study was supported in part by the Krasnoyarsk Scientific Fund (grant nos. 13G042 and 15G250) and by the Russian Fund of Basic Research (grant no. 03-04-48037). The authors thank Prof. T. Koike (Field Science Center for Northern Biosphere, Hokkaido University, Japan) for constructive comments on the manuscript and our collaborators at the Forest Science Laboratory of the V. N. Sukachev Institute of Forest, especially Dr. O. A. Zyryanova and Dr. T. N. Bugaenko for assistance in calculating projected cover values.

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