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Influences of canopy structure and physiological traits on flux partitioning between understory and overstory in an eastern Siberian boreal larch forest

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ABSTRACT

Boreal forests play an important role in the global balance of energy and CO_2. Our previous study of elaborate eddy covariance observations in a Siberian boreal larch forest, conducted both above the forest canopy and at the forest floor, revealed a significant contribution of latent heat flux (*LE*) from the cowberry understory to the whole ecosystem *LE*. Thus, in the present study, we examined what factors control the partitioning of whole ecosystem *LE* and CO_2 flux into the understory and overstory vegetation, using detailed leaf-level physiology (for both understory and overstory vegetation) and soil respiration property measurements as well as a multilayer soil-vegetation-atmosphere transfer (SVAT) model. The modeling results showed that the larch overstory's leaf area index (LAI) and vertical profile of leaf photosynthetic capacity were major factors determining the flux partitioning in this boreal forest ecosystem. This is unlike other forest ecosystems that tend to have dense LAI. We concluded that control of the larch overstory's LAI had a relationship with both the coexistence of the larch with the cowberry understory and with the water resources available to the total forest ecosystem.

1. Introduction

Boreal forests exist in a broad band across the northern hemisphere between the approximate latitudes of 50°N and 70°N. Globally, they account for about 25% of forest areas (Food and Agricultural Organization of the United Nations, 2005). Approximately 34% of boreal forests lie in North America, 22% in Europe to the west of the Urals, and 44% in northern Russia to the east of the Urals (Jarvis et al., 2001). These forests play significant roles in both global and regional climates by masking the high reflectance of snow and partitioning the available energy between sensible and latent heat fluxes (Bonan et al., 1992, 1995; Baldocchi et al., 2000a; Snyder et al., 2004; Bonan, 2008). Although mature boreal forests display low levels of annual carbon gain, such forests, nevertheless, store a large amount of carbon (Dixon et al., 1994; Malhi et al., 1999; Bonan, 2008). Some estimates, using inverse modeling from the latitudinal distribution of atmospheric CO_2 concentrations, suggest that the boreal forests represent a major terrestrial carbon sink in the northern hemisphere (Tans et al., 1990; Ciais et al., 1995; Bousquet et al., 1999).

However, a clear understanding of how the mass and energy exchange between atmosphere and boreal forests responds to environmental factors has yet to be achieved. This question is the focus of this investigation. It is predicted that boreal deforestation cools global climate by reducing net radiation through the increasing of surface albedo. However, many uncertainties, such as the effect of disturbance and stand age on surface fluxes, still remain (Bonan, 2008). Furthermore, as pointed out by Dolman et al. (2004), inverse atmospheric modeling techniques have produced contrasting results. Some have indicated a large carbon sink capacity for boreal forests (Bousquet et al., 1999), while others have concluded a neutral carbon balance (Rödenbeck et al., 2003), mainly because were constrained by the limitations of available measurements.

Boreal forests are particularly notable for the unique manner in which they store carbon in the soil. This is something that does not occur in other forest biomes. According to Malhi et al. (1999), 84% of the carbon is contained within the soil-based organic matter while the other 16% is contained within the active liv-

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ing biomass in the boreal forests, which largely contributes to the terrestrial carbon sink in the northern hemisphere (Bonan, 2008). This soil carbon storage also makes the boreal forests highly sensitive to global warming because the temperature rise could enhance the decomposition of the soil organic matter and stimulate respiration, and thus release a large amount of CO_2 (see Jarvis et al., 2001). Furthermore, the characteristic sparse overstory and dense understory vegetation of eastern Siberian boreal forests mean that latent heat and CO_2 fluxes at the forest floor become highly significant components of the whole canopy mass and energy exchange rates (Baldocchi and Vogel, 1996; Kelliher et al., 1997, 1999; Hollinger et al., 1998; Ohta et al., 2001; Hamada et al., 2004; Iida et al., 2009). It is of particular note that, since the surface temperature is among the major factors determining mass exchange at the surface and can be impacted by the partitioning of available energy to latent and sensible heat fluxes, thus the latent heat flux from the forest floor surface should be of primary concern.

The goal of this study, therefore, is to understand the energy and mass exchange processes between canopy space, air and understory vegetation in the boreal forest ecosystem. Toward this goal, using a multilayer soil-vegetation-atmosphere transfer (SVAT) model described by Kumagai et al. (2006) and detailed field measurements for flux partitioning conducted by Iida et al. (2009), we examined factors such as the overstory trees' canopy structure and leaf physiological traits to see which factors determine the partitioning of total canopy latent heat and CO_2 fluxes into understory and overstory vegetation. Prior to assessing the effect of the overstory tree characteristics on flux partitioning, the SVAT model was first validated using 10-day period data which was selected from 2-year field measurements conducted in a Siberian boreal larch forest.

2. Materials and methods

2.1. Site description

The experiment was carried out in an area of light taiga on the west bank of the middle reaches of the Lena River in eastern Siberia (62°15′N, 129°14′E, 220 m a.s.l.), 20 km north of the city of Yakutsk. The area is a continuous permafrost region. Previously, specific climatic data has been gathered for the region covering the period from 1998 to 2006 (Ohta et al., 2008). Here, the mean annual temperature was around −10 °C with a minimum temperature of below −50 °C occurring in mid-winter. During the summer season, the active layers overlying the permafrost thaw. The mean yearly maximum thawing depth has been around 147.0 cm. The mean annual precipitation was around 259.2 mm, but was also highly seasonal, ranging from around 69.0 mm for October–April to around 190.3 mm for May–September (Ohta et al., 2008).

Two stories of vegetation were apparent for the forest of the study site. The dominant overstory species was the deciduous coniferous larch (*Larix cajanderi* Mayr.), having a mean tree height of 20.5 m, a stand density of 808 trees ha^{-1}, and a basal area of 27.6 $m^2\,ha^{-1}$ (Matsumoto et al., 2008). The understory vegetation was very dense and low (<0.1 m), consisting of evergreen cowberry (*Vaccinium vitis-idaea* L.), which provided total ground cover. The leaf area index (LAI) of the larch was determined to be 1.6 and 2.0 by a plant canopy analyzer (LAI-2000, Li-Cor, Lincoln, NE) and the litter trap method (Iida et al., 2009), respectively. The LAI of the cowberry understory was measured by a destructive method and estimated to be 2.1 (Iida et al., 2009).

2.2. Meteorological and flux measurements

A 32-m tall tower was constructed at the site for micrometeorological and above-canopy flux measurements. The topography around the tower was almost flat, exhibiting only a slight northward incline. The following instruments were installed at the top of the tower: a solar radiometer (MS402F, EKO, Tokyo, Japan), an infrared radiometer (MS202F, EKO, Tokyo, Japan), a cup-anemometer (AC750, Makino, Tokyo, Japan) and a temperature (T_a) and a relative humidity (RH) sensor (HMP45D, Vaisala, Helsinki, Finland). To compute the net radiation above the canopy (R_n), the upward short-wave and long-wave radiation were measured using a solar radiometer (CM06F, Kipp & Zonen, Delft, Netherlands) and an infrared radiometer installed upside-down (MS201F, EKO, Tokyo, Japan), respectively. Forest floor environmental variables such as T_a, RH, wind speed and net radiation, were also measured, using a T_a and RH sensor (HMP45D), a cup anemometer (AC750) and a net radiometer (Q-7, REBS, Seattle, WA), respectively, at a height just above the understory vegetation. Micrometeorological data sets were recorded on a data logger (CR10X, Campbell Scientific, Logan, UT) sampling every 10 s and then producing an average for each 10-min period.

A three-dimensional sonic anemometer with an open-path CO_2/H_2O analyzer (LI-7500, Li-Cor, Lincoln, NE) was installed at each position at above ground heights of 32.0 m (WindMaster Pro, Gill, Hampshire, UK) and 3.3 m (R3-50, Gill). Wind speeds and a gas concentration time series were all sampled at 10 Hz (CR5000 datalogger, Campbell Scientific). All variances and covariances required for the eddy covariance flux estimates were computed from a 30-min averaging interval. The wind field coordinates were rotated so that the mean lateral and vertical wind speeds were zero over the 30-min periods. We also applied some corrections for turbulent and scalar readings such as for the effects of density fluctuation (as in Webb et al., 1980) and for the errors from the sonic anemometer angle of attack (as in Nakai et al., 2006). Details regarding turbulent data processing are described elsewhere (Nakai et al., 2006; Iida et al., 2009).

The eddy fluxes, as sensible and latent (LE) heat fluxes (W m^{-2}) and CO_2 flux (F_c: μmol $m^{-2}\,s^{-1}$), were observed at the above canopy sampling point and denote the fluxes of the whole ecosystem, consisting of fluxes from/into the larch overstory, the cowberry understory, and the soil. The eddy fluxes observed at the above the forest floor sampling point denote the fluxes from the cowberry and the soil alone. It is noteworthy, since soil evaporation is insignificant compared with the LE at both the above-canopy position (LE_o) and also at the above-forest floor position (LE_u) given the very dense cowberry cover, that, $LE_o - LE_u$ and LE_u can be considered to represent the transpiration rates from the larch and the cowberry, respectively. It has been reported that the detection of the eddy flux within forest canopies is particularly difficult (see Baldocchi et al., 2000b). We therefore confirmed the validity of the LE_u by examining the shapes of the power spectra and the co-spectra directly (Iida et al., 2009). Further information on the quality control and the energy closure of the LE_o and LE_u are presented in Iida et al. (2009).

The F_c above the canopy (F_{co}) is composed of the net assimilation rates of the larch and the cowberry added to both their autotrophic root respiration rates and to that of soil respiration. We assumed that the contribution of the within-canopy CO_2 storage flux to the net ecosystem CO_2 exchange (NEE) could be neglected because of the low LAI for the larch overstory. Nevertheless, in this study there remained some uncertainty in that F_{co} could be equal to the NEE. Because of the effect of weak winds and the intermittency of turbulence, some doubt also exists as to whether forest floor CO_2 flux (F_{cu}) observations could properly detect CO_2 balance between assimilation and respiration for the within-canopy air. Therefore,