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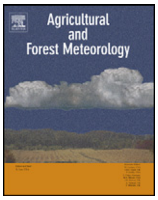

# Evapotranspiration from understory vegetation in an eastern Siberian boreal larch forest

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ABSTRACT

We measured evapotranspiration in an eastern Siberian boreal forest, in which the understory was cowberry and the overstory was larch, during the entire growing seasons of 2005 and 2006. We compared evapotranspiration from the understory vegetation above the forest floor $E_U$ with evapotranspiration from the whole ecosystem above the overstory canopy $E_O$. The $E_U/E_O$ ratio had a seasonal trend with a flat-bottomed U-shape during the growing season (4 May–30 September). High-$E_U/E_O$ ratios at the beginning and end of the growing season were observed because larch, one of the two sources of $E_O$, was a deciduous tree, while the understory was the evergreen cowberry. The mean daily $E_U$ values during the foliated period of larch (1 June–31 August) were 0.8 and 0.9 mm day$^{-1}$, or 51.4 and 51.8% of $E_O$ in 2005 and 2006, respectively. The understory vegetation was one of the most important components of the hydrologic cycle in this forest. A significant amount of $E_U$ was caused by plant physiological control, due to the aerodynamic conductance, which was much larger than the surface conductance, leading to a smaller decoupling coefficient. We found that 71% of $E_U$ was caused by the vapour pressure deficit above the forest floor.

## 1. Introduction

Forests cover approximately 30% of the total land surface of the Earth (FAO, 2005). They make effective use of radiation input, as the albedo is lower and net radiation is higher above forest canopies than above other land cover types (*e.g.*, McNaughton and Jarvis, 1983). Thus forests play an important role in energy and water partitioning processes. Approximately 25% of the global forest area is boreal forest, of which around 76% is in Russia (FAO, 2005). Investigation of water and energy exchanges between the forest and the atmosphere in boreal forests, especially those in Russia, is therefore essential to our understanding of the global hydrological cycle and energy balance.

Boreal forests have a number of features that make them different from forests in other climate regions: monotonous vegetation, relatively sparse main canopy trees, and dense understory vegetation. Black and Kelliher (1989) reviewed earlier publications that calculated the evapotranspiration from understory vegetation ($E_U$) using lysimeter or chamber methods, or through stomatal conductance measurements. They showed that the contribution of $E_U$ to evapotranspiration by the whole ecosystem ($E_O$) ranged from 8 to 65%. Thus the boreal forest ecosystem has two main sources of evapotranspiration: overstory trees and understory vegetation on the forest floor. To understand the water and energy exchange processes between the boreal forest ecosystem and the atmosphere, we must observe $E_U$ and evaluate its contribution to $E_O$.

Since the 1990s, many researchers have attempted to observe the latent and sensible heat fluxes above understory vegetation using the eddy-covariance (EC) method (Baldocchi and Meyers, 1991; Baldocchi and Vogel, 1996; Baldocchi et al., 1997, 2000a; Blanken et al., 1997). The EC has many advantages for $E_U$ measurements; namely, it allows direct evaluation, high time-resolution, spatially averaged observation. The EC method permits

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measurement of most of the turbulent eddies above the understory vegetation if the shapes of the power spectra and co-spectra are similar to those of the surface boundary layer (Baldocchi et al., 2000a), and if the energy closure ratio is similar to general values (*i.e.*, those reported by Wilson et al., 2002). Constantin et al. (1999) observed $E_U$ using the EC method in a boreal Swedish forest for two short periods: from 27 May to 23 June 1994, and from 27 June to 7 July 1995. They reported that $E_U$ contributed typically 10–15% of $E_O$. The Boreal Ecosystem–Atmosphere Study (BOREAS) project (Sellers et al., 1995) observed $E_U$ using the EC method over an entire growing season in a Canadian boreal aspen forest (Black et al., 1996; Blanken et al., 2001) and in a jack pine forest (Baldocchi et al., 1997). They reported $E_U/E_O$ ratios of 24% (Black et al., 1996), 27% (Blanken et al., 2001), and 20–40% (Baldocchi et al., 1997). Baldocchi et al. (2000b) noted that observations of $E_O$ for entire growing seasons are very rare in boreal forests. Indeed, for both $E_O$ and $E_U$, there have been very few observations performed over entire growing seasons, except for those of the BOREAS project.

A number of researchers have evaluated $E_U/E_O$ ratios in Siberian boreal forests. In a pioneering study, Kelliher et al. (1997) observed $E_O$ above a Siberian larch canopy using the EC method, and $E_U$ using lysimeters, during 9 days in summer. They reported that 50% of the total evapotranspiration emanated from the understory vegetation. A similarly high-$E_U/E_O$ ratio (54%) was observed in a Siberian pine forest (Kelliher et al., 1998). However, Kelliher and colleagues observed $E_U$ and $E_O$ by the EC method for only 18 days in mid-summer. Ohta et al. (2001) used the EC method to measure $E_O$ and sap-flow observations to measure the transpiration of overstory larch. They estimated $E_U$ as the difference between those values and reported an $E_U/E_O$ ratio of 35%. Hamada et al. (2004), who estimated $E_O$ by the EC method and $E_U$ by lysimeter measurements, reported that $E_U/E_O$ ranged from 25 to 50% in a Siberian pine forest. In all these studies, the results were based on short- or long-term $E_U$ data obtained by a low-time-resolution method (Kelliher et al., 1997; Hamada et al., 2004), on long-term but indirect $E_U$ estimations (Ohta et al., 2001), or on short-term $E_U$ measurements by the EC method (Kelliher et al., 1998). However, no studies can be found that have used the EC method to observe both $E_O$ and $E_U$ in Siberian boreal forest over an entire growing season. Thus, our aim was to observe $E_U$ directly for the entire growing season and to evaluate its quantitative contribution to the hydrologic cycle in Siberian boreal forests.

Because the contribution of $E_U$ to $E_O$ was likely to be large, it was important to clarify the factor controlling $E_U$ in boreal forests. Evapotranspiration is affected by the equilibrium evaporation $E_{eq}$, the "imposed" evaporation $E_{imp}$, and the decoupling factor $\Omega$, which indicates the relative importance of $E_{eq}$ (McNaughton and Jarvis, 1983). Baldocchi and Meyers (1991) and Baldocchi et al. (2000a) reported less coupling between $E_U$ and the available energy at the forest floor $AE_U$, which is the driving energy of $E_{eq}$ at the forest floor (*i.e.*, $E_{eq\text{-}U}$). They argued that large-scale eddies sweep moisture out of the canopy air space before $E_U$ can reach $E_{eq\text{-}U}$. As a result, $E_U$ is mainly determined by $E_{imp}$ at the forest floor (*i.e.*, $E_{imp\text{-}U}$) and is driven by the vapour pressure deficit. For Siberian boreal forests, Kelliher et al. (1997) obtained similar results as Baldocchi and Meyers (1991) and Baldocchi et al. (2000a), but their dataset spanned only 9 days. Long-term observations of $E_U$ and the micrometeorology above the understory vegetation are necessary to understand the factors that quantitatively control $E_U$ in Siberian boreal forest. As mentioned above, most boreal forest is located in Siberia; hence, this investigation may be essential for understanding the hydrologic cycle in boreal forests globally.

We measured $E_U$ by the EC method for two growing seasons (2005–2006) in a Siberian boreal forest. Our objectives were to (i) clarify the seasonal variation in the daily contribution of $E_U$ to $E_O$, (ii) evaluate the contribution of $E_U$ to $E_O$ quantitatively for entire growing seasons, and (iii) clarify the energy sources for $E_U$ and $E_O$.

## 2. Materials and methods

### 2.1. Site description

The observations were made at a site on the west bank of the middle reaches of the Lena River in eastern Siberia (62°15′18″N, 129°14′29″E; 220 m a.s.l.), approximately 20 km north of the city of Yakutsk. The site was situated in a continuous permafrost region referred to as the "Spasskaya Pad" experimental forest of the Institute for Biological Problems of the Cryolithozone, Russian Academy of Sciences (RAS). The annual mean air temperature was −10.4 °C (Dolman et al., 2004) and annual mean precipitation for the period from 1998 to 2006 was 259.2 mm (Ohta et al., 2008). During summer, the permafrost near the ground surface thawed, and its front retreated to >1 m in depth (Ohta et al., 2008). A meteorological observation tower 32 m high was installed at the site; the topography around the tower was mostly flat and inclined slightly northwards.

The experimental forest was typical light taiga. The dominant overstory species was deciduous coniferous larch (*Larix cajanderi*), which had a mean tree height of 18.0 m, basal area of 27.6 $m^2\ ha^{-1}$, and stand density of 840 trees $ha^{-1}$. The leaf area index (LAI) of the larch was determined to be 1.6 by a plant canopy analyser (LAI2000; LI-COR Inc., USA) and 2.0 by the litter trap method. The low-stand density allowed light to easily reach the forest floor, where very dense understory vegetation (evergreen cowberry, *Vaccinium vitis-idaea*) covered the ground completely. Although the cowberry understory was low (<0.1 m), it had an LAI of 2.1, as measured by the destructive method (Miyahara, 2005). Therefore, the LAI of the understory cowberry was almost equal to that of the overstory larch.

### 2.2. Observations

#### 2.2.1. Definition of $E_O$ and $E_U$

Micrometeorological observations were conducted on the tower during two growing seasons in 2005 and 2006. To evaluate evapotranspiration from the whole ecosystem ($E_O$) and from the understory ($E_U$) separately, we installed EC systems at heights of 32.0 and 3.3 m (Table 1). We used the EC method to measure $E_U$, and thus $E_U$ includes both the transpiration of the understory vegetation and the evaporation from soil. $E_O$ was composed of the transpiration of the larch overstory $E_{larch}$, $E_U$, and the change in latent heat storage below the height of 32.0 m $J_l$. Hence, $E_O = E_{larch} + E_U + J_l/\lambda$, where $\lambda$ is the latent heat of vapourisation of water.

#### 2.2.2. Environmental variables

Table 1 lists the sensors used in this study. We measured upward and downward shortwave radiation $S_u$ and $S_d$, upward and downward longwave radiation $L_u$ and $L_d$, downward photosynthetic photon flux density *PPFD*, air temperature $T_a$, and relative humidity *RH* on the observation tower. These variables were distinguished using subscripts of 'O' and 'U' for above the overstory and above the understory, respectively. For example, the upward shortwave radiation observed above the overstory was designated as $S_{u\text{-}O}$. Net radiation above the overstory ($R_{n\text{-}O}$) was calculated as the balance of four radiation components $R_{n\text{-}O} = (S_{d\text{-}O} - S_{u\text{-}O}) + (L_{d\text{-}O} - L_{u\text{-}O})$, and net radiation above the understory vegetation $R_{n\text{-}U}$ was observed with a radiometer. We measured the volumetric soil water content *VSWC* at five depths. Because the root system rarely extended below 0.5 m in depth (Ohta et al., 2008), the weighted mean of the *VSWC* was calculated for depths of 0–0.5 m ($VSWC_{0\text{-}50}$). Soil temperature $T_s$ was measured at seven depths. The soil