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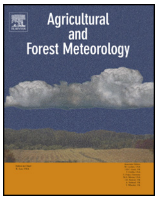

Effects of the expansion of vascular plants in *Sphagnum*-dominated bog on evapotranspiration

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ABSTRACT

Plant succession triggered by drainage, which results in the expansion or invasion of vascular plants, has been reported from many peatlands. However, the effects of the vascular plant's expansion on evapotranspiration (ET), which is a key component of the water balance of ombrotophic bog, are still contradictory. To investigate the effects, ET was measured at a *Sphagnum*-dominated bog and an adjacent transition peatland dominated by *Sasa*, dwarf bamboo, in Hokkaido Island, northern Japan, using the eddy covariance technique during the four growing seasons from 2007 through 2010. Cumulative gap-filled ET during a snow-free period of 6.5 months was 362 (2008) and 374 mm (2010) at the *Sphagnum* site and 300 (2008) and 372 mm (2010) at the *Sasa* site. In the mid-growing season (late June to mid-September) with the highest leaf area index (LAI) at the *Sasa* site, ET was 2.14 ± 0.03 (mean ± 1 standard deviation of the four years) and 1.92 ± 0.19 mm d^{-1}, respectively, at the *Sphagnum* and *Sasa* sites. ET was smaller at the *Sasa* site, except for 2010 with an unusual hot wet summer; mean air temperature and precipitation were higher than their 30-year normal values by 1.75 °C and 172 mm, respectively. At the *Sphagnum* site, ET was stable despite such interannual variation in meteorological conditions. However, ET increased significantly at the *Sasa* site in 2010 probably because of LAI increase due to the enhanced growth of *Sasa* plants. The ET increase at the *Sasa* site suggests that ET will increase at the *Sasa*-dominated area, if the future warming environment accompanies more precipitation.

1. Introduction

Peatlands are distributed worldwide with the total area of 4.16×10^6 km^2, of which more than 80% are localized in the temperate to subarctic regions of the Northern Hemisphere (Ryden and Jeglum, 2006). Northern peatland has accumulated soil organic carbon as peat under cool and waterlogged conditions over millennia, mainly during Holocene, up to 455–500 Pg (Gorham, 1991; Yu, 2012), which is equivalent to about 30% of global soil organic carbon (1550 Pg) (Lal, 2004). Therefore, a slight change of the huge carbon pool due to environmental perturbations can lead to a considerable change in the global carbon balance (Dorrepaal et al., 2009; Frolking et al., 2006; Heikkinen et al., 2004). As a result, northern peatland has attracted attentions from the viewpoint of global warming concerns during the last few decades (Charman et al., 2013; Frolking et al., 2011; Limpens et al., 2008; Mitsch et al., 2012).

The carbon balance of peatlands is strongly affected by local hydrology (Bozkurt et al., 2001; Fenner and Freeman, 2011; Limpens et al., 2008). Groundwater level (GWL), which usually remains high in natural peatlands, controls the thickness of an unsaturated peat layer with groundwater. Thus, lowering of GWL potentially enhances oxidative peat decomposition and, consequently increases carbon dioxide (CO_2) emissions to the atmosphere. Land-use change of natural peatlands for agriculture and forestry accompanies GWL lowering through drainage. In addition, lowered GWL tends to change the composition and productivity of plant communities; biomass of mesic vascular plants increases, leading to a decline of *Sphagnum* species chiefly by shading (Laine et al., 1995; Murphy et al., 2009; Talbot et al., 2010). Change in plant communities, which accompanies an increase in vascular plants at the expense of bryophytes and lichens, is also

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expected under warming climate (Berg et al., 2009; Walker et al., 2006; Ward et al., 2013). The increase of vascular plants will change the carbon and water balances of peatlands (Ward et al., 2013).

In peatlands, evapotranspiration (ET) is a key component of the water balance and much contributes to GWL variation, especially in ombrotrophic bogs (Lafleur, 2008). Comparative studies on ET from two adjacent bogs dominated by *Sphagnum* moss and covered or mixed with vascular plants, respectively, showed inconsistent results. Takagi et al. (1999), who applied the Bowen ratio/energy balance method, reported that a bog covered by invading dwarf bamboo (*Sasa palmata*) increased ET in comparison with a native open bog in northern Japan, which was attributed to larger leaf area index (LAI) of dwarf bamboo. In contrast, Strilesky and Humphreys (2012), who applied the eddy covariance method, reported that ET was smaller in a treed bog with stunted black spruce as an overstory than in an open bog in southern Canada. The different results probably arose from different biotic and abiotic conditions, including plant species, LAI, climate, hydrology and measurement duration. If the invasion of mesic vascular plants increases ET, bogs are forced to dry, and consequently the invasion would accelerate, resulting in a positive feedback. Also, GWL tends to decrease as the density of vascular plants increases because of increase in rainfall interception (Farrick and Price, 2009). Ongoing global warming potentially increases ET as a result of increasing water vapor deficit (VPD) due to temperature rise and shortened snow cover duration (Waddington et al., 2015), and also alters plant communities in peatlands (Walker et al., 2006; Ward et al., 2013). Because ET strongly affects the carbon pool of peatlands via GWL, it is crucial to understand the effects of the vegetation alteration on ET. However, our knowledge on the effects is still insufficient owing to a limited number of related field studies. Therefore, well-designed comparative experiments at adjacent peatlands are essential (Moore et al., 2013).

We measured sensible heat (H) and latent heat (LE) fluxes using the eddy covariance technique and determined ET and energy balance at two adjacent sites, where *Sphagnum* moss and mesic dwarf bamboo (*Sasa*) dominate, respectively, in an ombrotrophic bog area (Takagi et al., 1999) in Hokkaido, the northernmost island of Japan, during four growing seasons from 2007 through 2010, including a record-breaking hot summer in 2010 (Otomi et al., 2012). In the ombrotrophic bog area, *Sasa* plants have been expanding since the 1960s, when a drainage channel was excavated (Tsujii, 1963). *Sasa* expansion after drainage is common in many other bog areas in Hokkaido Island (Fujita, 2006). Here, we show the results of the field experiment and discuss the seasonal and interannual variations of ET in combination with phenology and climatic variability, and environmental control on ET using bulk surface conductance. Finally, we assess whether the invasion of *Sasa* plants into a *Sphagnum*-dominated bog increases ET and discuss the impact on ET of the abnormally hot summer that is predicted in the near future under ongoing global warming.

2. Materials and methods

2.1. Study area

The field experiment was conducted at a *Sphagnum*-dominated open bog and an adjacent *Sasa*-dominated transition peatland (45°06′ N, 141°42′ E; 6–7 m alt.) in Sarobetsu Mire with the total area of 6658 ha, in which bog with flat lawn is the dominant peatland type (Fujita et al., 2007), in northern Hokkaido Island, northern Japan. The mire was bordered by drainage ditches, a river and pastures. About 6-m-thick peat has accumulated for 4000–5000 years (Ohira, 1995; Sakaguchi et al., 1985). *Sphagnum papillosum* Linbd., *Sphagnum magellanicum* Brid. and *Carex middendorffi* were dominant in the *Sphagnum*-dominated bog (*Sphagnum* site), whereas *Sasa palmata* densely covered *Sphagnum* species on the ground along with *Myrica gale* L. var. *tomentosa* C.D.C and *Ilex crenata* Thunb. var. *radicans* (Nakai ex H. Hara) Murai as overstory in the *Sasa*-dominated peatland (*Sasa* site) (Fujimura et al., 2012). The canopy heights ranged from 0.2 (*Sphagnum*) to 0.45 m (*Sasa*) at the maximum. The ground surface was partly covered with *Carex*'s leaf litter in spring at *Sphagnum* site, whereas the ground was densely mulched with *Sasa*'s leaf litter throughout the growing season at *Sasa* site. *S. palmata* spreads rhizomes for vegetative propagation. The rhizomes and roots of *Sasa* plants penetrated 0.3–0.4 m into peat soil, yet they concentrated within the top 0.2 m (Takakuwa and Ito, 1986). *Sasa* plants began to expand into the open bog area in the 1960s with the excavation of drainage ditches for agriculture (Tsujii, 1963). The *Sasa*-dominated area has increased by 15.8% between 1977 and 2003 (Fujimura et al., 2013); the *Sasa* expansion was attributable to the alteration of groundwater regime through drainage (Fujimura et al., 2012; Takada et al., 2012).

Annual mean air temperature and annual precipitation are 6.1 °C and 1073 mm (1981–2010) at Toyotomi meteorological observatory, which is located about 6 km east of the study sites. The minimum and maximum mean monthly temperatures are −6.5 (January and February) and 19.6 °C (August), respectively. Precipitation in the growing season from May through October accounts for 57% of annual precipitation. Annual maximum snow depth reaches about 1 m. The deep snow accumulation inhibits the development of *Sphagnum* hummocks (Yabe and Uemura, 2001; Yazaki and Yabe, 2012).

2.2. Field measurement

A small mast was built for the following measurement at *Sphagnum* site and the adjacent *Sasa* site, respectively; the location of *Sphagnum* site is the same as site B in the work by Takagi et al. (1999). The two eddy covariance towers were located about 600 m apart. Fetch for flux measurement was more than 200 m in all directions for both masts.

Eddy fluxes of sensible heat (H) and latent heat (LE) were measured on the masts of *Sphagnum* and *Sasa* sites, respectively, during the four snow-free periods from late June to early November in 2007, late April to mid-November in 2008, mid-April to early November in 2009 and late April to early November in 2010. Data were missing after October in 2007 at *Sphagnum* site and after mid-September in 2009 at *Sasa* site owing to system malfunction. A sonic anemometer-thermometer (CSAT3; Campbell Scientific Inc., Logan, UT, USA) and an open-path CO_2/H_2O analyzer (LI7500; LICOR Inc., Lincoln, NE, USA) were used to measure H and LE. Sensor signals were recorded using a datalogger (CR1000; Campbell Scientific Inc.) at 10 Hz. The open-path analyzer was calibrated every year using a dew-point generator (LI810; LICOR Inc.) in a laboratory.

Global solar radiation (R_g) and net radiation (R_n) were measured with a radiometer (CNR-1; Kipp & Zonen, Delft, the Netherlands) at a height of 1.8 m. Air temperature and relative humidity were measured with a platinum resistance thermometer and a capacitive hygrometer (HMP45; Vaisala, Helsinki, Finland) installed in a non-ventilated radiation shield (DTR503A; Vaisala) at a height of 1.5 m. Precipitation was measured with a tipping-bucket rain gauge (TE525; Campbell Scientific Inc.) at a height of 1.5 m only at *Sasa* site. Wind velocity and direction were measured with a cup anemometer and a wind vane (03002-47A; R. M. Young Co., Traverse, MI, USA) at a height of 2.3 m only at *Sasa* site. Soil temperature was measured with thermocouples at depths of 2, 5, 10 and 40 cm. Volumetric soil water content (SWC) was measured with a TDR sensor (CS616; Campbell Scientific Inc.) buried at a depth of 5 cm and calibrated using the oven-drying method. Heat flux was measured with a heat flow transducer (HFT1.1; REBS, Belleuve,