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Minor contribution of overstory transpiration to landscape evapotranspiration in boreal permafrost peatlands

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Abstract. Evapotranspiration (ET) is a key component of the water cycle, whereby accurate partitioning of ET into evaporation and transpiration provides important information about the intrinsically coupled carbon, water, and energy fluxes. Currently, global estimates of partitioned evaporative and transpiration fluxes remain highly uncertain, especially for high-latitude ecosystems where measurements are scarce. Forested peat plateaus underlain by permafrost and surrounded by permafrost-free wetlands characterize approximately 60% (7.0 × 10^7 km^2) of Canadian peatlands. In this study, 22 Picea mariana (black spruce), a characteristic tree species of the boreal ecozone, were instrumented with sap flow sensors within the footprint of an eddy covariance tower measuring ET of a forest-wetland mosaic landscape. Sap flux density (J_S), together with remote sensing and in situ measurements of canopy structure, were used to scale J_S to overstory transpiration (T_{BS}). Black spruce trees growing in nutrient-poor permafrost peat soils were found to have lower mean J_S than those growing in mineral soils and contribute less than 1% to landscape ET. Climate change-induced forest loss and the expansion of wetlands may further minimize the contributions of T_{BS} to ET, and increase the contribution of standing water.

1. Introduction

Evapotranspiration (ET) is a key component of the water cycle and can be partitioned into biotic and abiotic components (e.g., Wang and Dickinson (2012)). The former consists of transpiration, i.e., the loss of water primarily from plant stomata, while the latter encompasses evaporation from plant interception, soil and open water evaporation, as well as snow sublimation (Lawrence et al., 2007; Fatichi and Pappas, 2017). Accurate partitioning of ET into evaporation and transpiration components provides important information to validate and improve the simulation of carbon, water, and energy fluxes within terrestrial ecosystem models (Lawrence et al., 2007;
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Wang and Dickinson, 2012; Fatichi et al., 2015; Fatichi and Pappas, 2017). Increasingly, accurate partitioning of water fluxes at regional scales are also required to reliably quantify and manage water resources under rapidly changing climatic and environmental conditions (Bonan, 2008; Schaefer et al., 2012). Numerous studies have partitioned ET into its component fluxes (e.g., Jasechko et al. (2013), Good et al. (2015)). However, global estimates remain highly uncertain (e.g., Coenders-Gerrits et al. (2014), Wang et al. (2014)). Moreover, most of the global scale analyses focus on temperate regions, with ET partitioning in northern boreal and high-latitude ecosystems remaining under-represented due to limited available information (e.g., Good et al. (2015), Jasechko et al. (2013), Schlesinger and Jasechko (2014), Fatichi and Pappas (2017)).

Peatlands are found throughout the boreal biome and are defined as ecosystems with more than 40 cm of accumulated organic material. Distinct peatland classes can be defined based on their hydrology, vegetation, and chemical composition (National Wetlands Working Group, 1997), and further described by the presence or absence of permafrost, i.e., perennially cryotic ground (Zoltai and Tarnocai, 1975). Peatlands of high boreal and low subarctic regions comprise 58% of the total peatland area in Canada (Figure 1b). Such high-latitude peat landscapes are often characterized by forested permafrost peat plateaus that are elevated approximately 1 m above surrounding wetlands, mostly patterned and/or flat fens, and collapse-scar and/or flat bogs (Zoltai and Tarnocai, 1975). Permafrost only occurs under peat plateaus, being absent from adjacent fens and bogs.

Climate change-induced permafrost thaw could potentially influence boreal and subarctic peatland land-surface interactions at the regional scale (Grosse et al., 2016). Along its southern limit, permafrost is relatively warm and thin (Smith et al., 2005). In recent decades,
warming air temperatures have accelerated the rate of permafrost thaw (Baltzer et al., 2014; Chasmer and Hopkinson, 2016; Grosse et al., 2016; Quinton et al., 2011) impacting forest composition, structure and function (Baltzer et al., 2014; Jorgenson et al., 2013; Lara et al., 2016), and thus carbon, water and energy fluxes (Grosse et al., 2016; Helbig et al., 2016b; Turetsky et al., 2002). Thawing sporadic discontinuous permafrost, i.e., permafrost occurring on <50% of the landscape, has been shown to induce surface subsidence, thereby replacing forests (i.e. peat plateaus) with permafrost-free wetlands (referring to fens and bogs in this study) (Baltzer et al., 2014; Jorgenson et al., 2013; Lara et al., 2016). The post-thaw wetland water table is close to the ground surface allowing open water or energy-limited ET, in contrast to the raised peat plateaus that are water-limited. Land cover conversion from mostly black spruce dominated peat plateaus with permafrost to treeless, permafrost-free wetlands may therefore increase landscape ET across parts of northwestern Canada (Helbig et al., 2016b).

Here, we use tree-level sap flux density measurements ($J_S$; i.e., sap flow per unit of sapwood area) of black spruce, a widespread boreal tree species, together with site-specific tree allometry and a canopy height model (CHM) derived from Light Detection and Ranging (LiDAR) to estimate overstory transpiration over a boreal peat landscape with sporadic permafrost in northwestern Canada. Upscaled overstory transpiration is then compared with landscape ET estimates from concurrent eddy covariance measurements. The objectives of this study are (i) to quantify the contribution of black spruce transpiration ($T_{BS}$) to landscape ET, and (ii) to discuss the impacts of a shift in $T_{BS}$/ET as a result of permafrost thaw-induced boreal forest loss and wetland expansion.

2. Materials and methods
2.1. Study site

The study site is a boreal forest stand of ca. 0.75 km² on permafrost peat plateaus with interspersed permafrost-free bogs and fens, situated in the southern portion of the Scotty Creek watershed, Northwest Territories (NT), Canada (61.17°83°N, 121.17°25°W) (Figure 1a). Scotty Creek is a hydrologically well-characterized watershed south of Fort Simpson, NT under the influence of rapidly thawing sporadic permafrost (Quinton et al., 2011). The climate of the region is characterized by short summers and long, cold winters with a mean annual air temperature and a total precipitation of -2.8 °C and 390 mm, respectively (1981 – 2010 climate normals, Fort Simpson, Environment Canada, 2014). Mean annual air temperature has increased since the 1970’s, contributing to accelerated permafrost thaw increasing from 0.19% (of total basin area) per year (1970 - 2000) to 0.58% per year (2000 - 2015) (Chasmer and Hopkinson, 2016). The increasing rate of permafrost disappearance has caused expansion of bogs and fens at the expense of forested peat plateaus at Scotty Creek, and across the southern Taiga Plains ecozone (Baltzer et al., 2014; Chasmer and Hopkinson, 2016; Helbig et al., 2016b). Similar landscapes to Scotty Creek are widespread throughout the Canadian and Russian boreal ecozone (Olefeldt et al., 2016), with a reported 21% of the global boreal forest classified as lowland forest overlying permafrost or thick overburden (Helbig et al., 2016a).

Forested permafrost peat plateau vegetation consists of a *Picea mariana* (black spruce) dominated overstory and sporadic *Larix laricina* (tamarack), which combined constitute >95% of stems >1 cm (J L Baltzer, unpublished data). *Picea glauca* (white spruce), *Pinus banksiana* (jack pine), *Populus tremuloides* (trembling aspen), and *Betula neoalaskana* (Alaskan paper birch) also occasionally occur. The understory is composed of *Betula spp.* (birch) shrubs, *Rhododendron groenlandicum* (bog Labrador tea), *Andromeda polifolia* (bog rosemary), *Cladina*
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spp. (reindeer lichen), Pleurozium schreberi (feather moss) and Sphagnum spp. (Garon-
Labrecque et al., 2015). The average tree height ($H$) is 2.2 m ± 1.2 and stand density is ca. 0.12
stems m$^{-2}$ (peat plateaus = 0.18 stems m$^{-2}$, bogs = 0.07 stems m$^{-2}$, fens = 0.03 stems m$^{-2}$), as
extracted from the CHM. As the CHM does not differentiate between different tree species, all
trees were assumed to be black spruce, which dominate the landscape (ca. 83%, J L Baltzer,
unpublished data). Leaf Area Index (LAI; LAI-2200 Plant Canopy Analyzer, Li-COR
Biosciences, Lincoln, NE, USA) was estimated (Sonnentag et al., 2007) for over- (0.61 m$^{2}$ m$^{-2}$ ±
0.34 (one standard deviation)) and understory (0.68 m$^{2}$ m$^{-2}$ ± 0.25) vegetation ($n = 31$), in July
2013. Ericaceous shrubs and Sphagnum spp. generally dominate bogs, while shrubs, sedges,
grasses, and brown mosses dominate fens (Garon-Labrecque et al., 2015).

2.2. Sap flux density measurements

During a portion the 2013 growing season (May 31 to July 13), 22 black spruce trees of similar
size (10.0 - 11.9 cm diameter at breast height) were instrumented at breast height (1.3 m) with
heat-ratio-method sap flow sensors (HRM; SFM1 Sap Flow Meter, ICT International, Armidale,
New South Wales, Australia; following Burgess et al. (2001)). All trees were located in the
interior of peat plateaus, avoiding edges where tree function has been shown to be reduced
(Patankar et al., 2015). These trees were selected to span the range of environmental conditions
(e.g. nutrient gradient) present at Scotty Creek and thus capture within-site variability in sap
flow. Most of the instrumented trees were located within or near the landscape eddy covariance
flux tower footprint (Figure 1a). Heat pulse sap velocity ($V_s$, cm hr$^{-1}$) was calculated from the
Sap Flow Tool software (ICT International Armidale, New South Wales, Australia). Sap velocity
measured at the first thermistor (length equal to 12.5 mm) was used in our study, as the second
thermistor (length equal to 27.5 mm) was located in non-conducting wood tissues (heartwood).

\[ J_S \ (\text{gH}_2\text{O m}^{-2} \text{s}^{-1}) \] was derived from \( V_S \) every 30 minutes, assuming one unit of sapwood area and water density was equal to 1000 kg m\(^{-3}\).

2.3. Eddy covariance and supporting measurements

Boreal forest-wetland “landscape” ET (\( \text{ET}_{\text{LAND}} \); 2013 – 2016) and “wetland” ET (\( \text{ET}_{\text{BOG}} \); 2014 – 2016) were obtained from nested eddy covariance measurements (Helbig et al., 2016b), installed in August 2012 and 2013 respectively. Two towers were equipped with the same flux and micrometeorological instrumentation, including an infrared \( \text{CO}_2/\text{H}_2\text{O} \) gas analyzer (EC150; Campbell Scientific Inc., Logan, UT, USA) and a three-dimensional sonic anemometer (CSAT3A; Campbell Scientific Inc.). These were mounted on a 15-m tower located on the forested peat plateau, and approximately 100 m north at the bog site on a 2 m tripod, respectively. A detailed description of the eddy covariance set-up at Scotty Creek is given by Helbig et al. (2016b). The 90% landscape and bog flux footprints were derived from a 2D footprint parameterization (Kljun et al., 2015), which were used to quantify the mean growing season ET flux footprint contributions from forested peat plateaus \((a = 51 \%)\) and wetlands \((b = 49 \%)\) (see equation 1 below). For the landscape tower, all fluxes within the footprint with >5% contributions from the lake were filtered. Contributions from fens never exceeded 10%, and were aggregated with the bog contribution for a total wetland flux. For the wetland tower, all fluxes with contribution greater than 5% from the forest were similarly filtered. To estimate \( \text{ET}_{\text{BOG}} \) for 2013, when only \( \text{ET}_{\text{LAND}} \) and sap flux density were measured, we applied a linear relationship between concurrent \( \text{ET}_{\text{LAND}} \) and \( \text{ET}_{\text{BOG}} \) measurements during the other years following Helbig et al. (2016b). We used the mean slope and intercept for the three-year period: \( 1.26 \pm 0.18 \) and -
1.68 ± 0.24 mg H$_2$O m$^{-2}$ s$^{-1}$ ($n = 3$), respectively (see Supplementary material Figure S1).

Measured ET$_{\text{LAND}}$ in 2013 was then partitioned to derive forest (i.e., peat plateau) ET (ET$_{\text{FOR}}$) using the mean weighted flux footprint contributions for the two land cover types (forest [FOR] and wetland [BOG]) and the derived ET$_{\text{BOG}}$:

$$ET_{\text{LAND}} = aET_{\text{FOR}} + bET_{\text{BOG}} \quad (1)$$

Photosynthetically active radiation (PAR, µmol m$^{-2}$ s$^{-1}$; PQS1, Kipp and Zonen, Delft, the Netherlands), vapour pressure deficit (VPD, hPa; Rotronic AG, Bassersdorf, Switzerland), and air temperature (°C; HC2-S3, Rotronic AG, Bassersdorf, Switzerland) were measured at the landscape tower above the forest canopy at 30-minute intervals. Precipitation (mm) was also measured at 30-minute intervals using a tipping bucket rain gauge (TR-5251, Texas Electronics Inc., Dallas, Texas, USA) located within the landscape flux footprint.

2.4. Allometric relationships

Allometric field surveys in the landscape flux footprint were conducted in 2012 ($n = 100$), 2015 ($n = 51$) and 2016 ($n = 47$) to establish the relationship between black spruce $H$ (m) and DBH (cm). Both $H$ and DBH were non-normally distributed and heteroscedastic, and therefore subsequently log-transformed. A site-specific relationship (Figure 2) was developed to relate $H$ and DBH ($\text{DBH} = 10^{0.067 \times H^{0.989}}, r^2 = 0.67, p < 0.001, n = 198$). A correction factor of 1.054 was applied to account for the systematic bias to the base logarithm introduced by the log-transformation (Sprugel, 1983).

The allometric relationship between DBH and sapwood area ($A_s$, cm$^2$) was similarly log-transformed using data from the 2016 survey. Sapwood thickness was identified visually after
examining tree cores against the sunlight (mean 10.0 mm +/- 6.1, n = 47). Sapwood was relatively wet and translucent in comparison to heartwood. This relationship was best described by the function \( A_S = 10^{-0.633} \times DBH^{1.848} \) (\( r^2 = 0.76, p < 0.001 \)) with a correction factor of 1.059 (Figure 2b).

2.5 Upscaling tree-level sap flux density to landscape evapotranspiration

A LiDAR dataset of Scotty Creek at 1 m\(^2\) spatial resolution was acquired in 2010 and used to produce a CHM (Chasmer et al., 2014; Chasmer et al., 2011). Grid cells with canopy heights <1 m were excluded from the analysis as these represent understory and ground surface vegetation structures. Per 1 m\(^2\) CHM grid cell, sap flux density was scaled from individual tree- \( (J_S) \) to overstory- \( (T_{BS}) \), and thus landscape-level, based on the equation:

\[
T_{BS} = J_S \frac{A_S}{A_G}
\]

where \( J_S \) is the average half-hourly sap flux density (g H\(_2\)O m\(^{-2}\) 30 min\(^{-1}\)), \( A_S \) is the sapwood area per grid cell (m\(^2\)), and \( A_G \) is the grid cell area (m\(^2\)). We assume a maximum stem density of one tree per m\(^2\), i.e., a CHM cell cannot contain more than one individual, which is supported by a stand density of <1 stem m\(^{-2}\). Sapwood area was calculated from the footprint-specific allometric relationships between \( H \), DBH, and \( A_S \) using the CHM. To address potential uncertainties in sapwood depth measurements in resinous tree species (e.g., Van Herk et al. (2011)), we examined also an hypothetical scenario where \( A_S \) equalled the cross-sectional area \( (A_{CS}) \) for trees with a DBH ≤ 5.4 cm (i.e., the average of the studied trees in Van Herk et al. (2011)) and \( A_S = 0.5A_{CS} \) for trees with a DBH ≥ 5.4 cm. This approach allowed us to obtain an upper limit of scaled \( T_{BS} \) and of its contribution to ET\(_{LAND}\).
2.6 Uncertainty analysis

Possible sources of uncertainty in $T_{BS}$ are (i) an underestimation of $H$ from the CHM due to low/no returns from the apices of narrow black spruce crowns, (ii) uncertainties in the derived allometric equations, and (iii) variability of $J_S$ between trees. These uncertainties were addressed using a Monte Carlo uncertainty analysis (MC-UA) of the scaling procedure. LiDAR-derived canopy height was assumed to be approximately 10% lower than measured tree height as found by Hopkinson et al. (2005). The CHM uncertainties were implemented in the MC-UA by replacing each grid cell value with a canopy height sampled from a normal distribution with mean equal to the original CHM value of this grid cell and standard deviation of 10%. The allometric relationships derived in Figure 2 were applied to the CHM to estimate transpiration fluxes from the area within the flux footprint, and included the range of error associated with underestimated canopy height (see Supplementary Material Figures S3-6). Uncertainties arising from using mean $J_S$ were addressed by randomly sampling from a normal distribution with the standard deviation of $J_S$ from all instrumented trees per time step. Per MC-UA iteration (100 in total), $T_{BS}$ was calculated for each CHM grid cell using equation 2 and summed to determine total footprint $T_{BS}$. Black spruce transpiration for the footprint is given as the mean $T_{BS}$ of the iterations +/- the standard deviation.

3. Results and discussion

3.1. Daily and seasonal patterns of sap flux density

Total precipitation at Scotty Creek during the study period (May 31 to July 13 2013) amounted to 88.8 mm, with mean air temperature of 17.6 °C (minimum = 4.1 °C, maximum = 32.2 °C) (Figures 3a,f). Maximum air temperature and VPD occurred late-June to early-July, while
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maximum PAR was observed early-June to early-July (Figures 3d-f). Black spruce $J_S$ was
greater than zero throughout the day, most likely due to the long photoperiod (~22 h) (Patankar
et al. 2015; Figures 3b-e). Maximum $J_S$ occurred approximately a month after snowmelt in
early-May (Connon et al., 2015) and slowly declined over the remainder of the growing season,
with the exception of days following rainfall (Figures 3a,b). On days with larger precipitation
events (Figure 3a), $J_S$ approached zero and differed from the typical diurnal pattern (Figure 3b).

A similar daily and seasonal flux pattern was observed for ET$_{LAND}$ (Figure 3c).

In comparison to previous black spruce sap flux density studies (Table 1), black spruce at
Scotty Creek had lower mean daily $J_S$ (minimum = 0.1, mean = 8.0, maximum = 21.7 in gH$_2$O
m$^2$ s$^{-1}$). Angstmann et al. (2013) found similarly low mean daytime $J_S$ in black spruce growing
in peat soils. In contrast, $J_S$ reported for smaller-DBH black spruce growing in mineral soils were
about ten times higher (Ewers et al., 2005; Van Herk et al., 2011). This difference may be due to
a number of environmental factors controlling the magnitude of $J_S$, including stand structure
(Angstmann et al., 2012; Ewers et al., 2005), moisture gradients (Angstmann et al., 2013;
Bovard et al., 2005; Oren and Pataki, 2001), soil nutrients, and presence or absence of
permafrost (Iijima et al., 2014; Patankar et al., 2015). In particular, Scotty Creek has the lowest
overstory LAI, canopy height and stand density among the reported studies in Table 1, and is
additionally underlain by nutrient-poor, peat soils. Low nitrogen availability of similar black
spruce forests growing on permafrost-affected peat soils in Alaska has been recently reported
Finger et al. (2016). Additionally, black spruce rooting depth is commonly limited to the top 20
cm of soil (Finger et al., 2016; Gale and Grigal, 1987) controlling access to water as the growing
season progresses (Patankar et al., 2015; Sniderhan and Baltzer, 2016). It should also be noted
that $J_S$ may also vary depending on measuring technique, e.g. HRM (this study), versus Granier-
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style sensors (Table 1) and/or data corrections applied *a posteriori* to account for possible contact of the sap flow probes with non conductive tissues (e.g., Steppe *et al.* (2010)).

3.3. Evapotranspiration and black spruce transpiration

Mean daily ET\textsubscript{LAND} (+/- one standard deviation) per m\textsuperscript{2} of the footprint in 2013 was 2.33 mm d\textsuperscript{-1} +/- 0.77 and was partitioned into ET\textsubscript{FOR} = 1.72 mm d\textsuperscript{-1} +/- 0.57 and ET\textsubscript{BOG} = 2.92 mm d\textsuperscript{-1} +/- 0.97. Mean daily T\textsubscript{BS} was 0.02 mm d\textsuperscript{-1} +/- <0.01 composed of 0.03 mm d\textsuperscript{-1} +/- 0.01 from forested areas (i.e., peat plateaus, T\textsubscript{BS-FOR}) and <0.01 mm d\textsuperscript{-1} from wetlands (T\textsubscript{BS-BOG}). Overall, T\textsubscript{BS} contributed 0.9 % to ET\textsubscript{LAND} (1.9% to T\textsubscript{BS-FOR} and 0.4 % to T\textsubscript{BS-BOG}; Figure 4). The upper limit of T\textsubscript{BS} and of its contribution to ET\textsubscript{LAND} indicated that T\textsubscript{BS} may account for up to 2.1% of ET\textsubscript{LAND}, and T\textsubscript{BS-FOR} for 4.5% of ET\textsubscript{FOR}; however, T\textsubscript{BS} remains a minor contribution to ET. These findings suggest that black spruce forests growing on peat soils, especially with permafrost, may contribute much less to ET than their mineral soil counterparts (Table 1). In contrast to sites with greater canopy coverage, the sparse tree density at Scotty Creek allows plenty of light to penetrate into the black spruce canopy and to reach the understory layer (Chasmer *et al.*, 2011), potentially allowing understory transpiration (i.e. Labrador tea, birch, moss, lichen) to play a larger role in the landscape water balance (Lafleur, 1992).

3.3. Climate change and evapotranspiration in boreal permafrost peatlands

Accelerated rates of permafrost thaw, and continued climate warming have already resulted in landscape changes through forest loss and the expansion of wetlands along the southern limit of permafrost (Baltzer *et al.*, 2014; Helbig *et al.*, 2016a). For example, the recent study of Chasmer and Hopkinson (2016) projects a complete loss of permafrost from the Scotty Creek basin by *ca.*
2044. Helbig et al. (2016b) found that with permafrost thaw-induced wetland expansion the partitioning of available energy will shift from sensible heat flux more toward to latent heat flux and thus ET, as the flux from a bog-only flux footprint is 1.54 times greater than the landscape flux footprint (ca. 50% wetland and ca. 50% forest). Continued wetland expansion across these regions would increase ET_{LAND}, mainly due to an increase in open water and moss evaporation, and even further minimize the contribution of black spruce to the water balance. Additionally, root sap flux density has been shown to be significantly lower in black spruce trees near peat plateau edges in the peat plateau-wetland transition zone compared with interior peat plateau trees (Baltzer et al., 2014; Patankar et al., 2015). Thus, it may be surmised that with the increase in both wetland expansion and forest fragmentation, combined with growth reductions that have been attributed to active layer thickening (Sniderhan and Baltzer, 2016), the contribution of $T_{BS}$ to ET_{LAND} will even further decrease. However, in contrast to other forested systems, loss of trees in a permafrost boreal peat landscape likely does not directly alter landscape ET, or account for the observed increase in basin runoff, attributed to the increasingly interconnected wetland features (Connon et al., 2014) that promote ET. Additionally, while forest loss is not likely to significantly alter water fluxes directly, the associated collapse of peat plateaus with permafrost thaw is expected to increase water availability to the moss surface and enhance total evaporation, as demonstrated by the systematic difference in ET_{LAND} and ET_{BOG} in this study, and the findings of Helbig et al. (2016b). Increased drainage and a future drier state in this system may permit the recovery of forests, and potentially enhance the contribution of overstory transpiration to ET.

4. Conclusion
In this study, we quantified the contribution of black spruce growing on permafrost peat soils to the overall water flux for a boreal peat landscape. We demonstrate that, while overstory vegetation (i.e., black spruce) is not a significant contributor (<1% of landscape ET flux), the loss of black spruce due to accelerating permafrost thaw could alter the partitioning of energy within this broad landscape. When compared with black spruce growing on mineral soils and/or at lower latitudes, black spruce growing on peat plateaus with permafrost has the lowest sap flow, likely resulting in the minor contribution of overstory to landscape ET. As forested permafrost peat plateaus along the southern limit of permafrost transition into permafrost-free and treeless wetland environments (i.e., bogs and fens), it will become increasingly important to quantify contributions from various shrub species, peatland sedges and mosses, and open water areas.

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CONTRIBUTION OF OVERSTORY TRANSPIRATION IN A BOREAL PERMAFROST PEATLAND


Table 1. A non-exhaustive literature review of reported values of black spruce sap flux density in the boreal region, including study location, soil type, permafrost presence (PF, Yes/No), tree sap flux density ($J_s$ in gH$_2$O m$^{-2}$ s$^{-1}$), diameter at breast height (DBH, cm), mean tree height ($H$, m), sapwood area ($A_s$, cm$^2$), stem density (D, stems m$^{-2}$), leaf area index (LAI, m$^2$ m$^{-2}$), air temperature (°C) and mean annual precipitation (Prec., mm).
<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Soil</th>
<th>PF</th>
<th>n</th>
<th>JS</th>
<th>DBH</th>
<th>H</th>
<th>As</th>
<th>D</th>
<th>LAI</th>
<th>T</th>
<th>Prec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study (SFS)</td>
<td>61°18'N, 121°18'W</td>
<td>peat</td>
<td>Y</td>
<td>22</td>
<td>8.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>88.8</td>
</tr>
<tr>
<td>This study (CHM)</td>
<td>61°18'N, 121°18'W</td>
<td>peat</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>2.8</td>
<td>2.2</td>
<td>1.8</td>
<td>0.12</td>
<td>0.6</td>
<td>-2.7</td>
<td>390</td>
</tr>
<tr>
<td>Angstmann et al. (2013)</td>
<td>55°55'N, 98°21'W</td>
<td>peat</td>
<td>N</td>
<td>117</td>
<td>18.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-</td>
<td>-</td>
<td>2.1</td>
<td>0.48</td>
<td>2.7&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.8</td>
<td>439</td>
</tr>
<tr>
<td>Van Herk et al. (2011)</td>
<td>55°53'N, 98°20'W</td>
<td>mineral</td>
<td>N</td>
<td>16</td>
<td>61.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.5</td>
<td>-</td>
<td>2.7</td>
<td>0.20</td>
<td>3.1</td>
<td>-3.2</td>
<td>517</td>
</tr>
<tr>
<td>Ewers et al. (2005)</td>
<td>55°53'N, 98°20'W</td>
<td>mineral</td>
<td>N</td>
<td>38</td>
<td>86.7&lt;sup&gt;d&lt;/sup&gt;</td>
<td>6.9</td>
<td>6.9</td>
<td>-</td>
<td>0.39</td>
<td>3.6</td>
<td>0.8</td>
<td>439</td>
</tr>
</tbody>
</table>

<sup>a</sup> from Angstmann et al. (2012)

Superscripts refer to the time period over which mean JS was calculated: <sup>a</sup> over 24 h period 0000 – 2359 h June - July, <sup>b</sup> over 12 h period 0600 – 1800 h; mean of all stands, <sup>c</sup> over 24 h period May – September; mean given for outside control trees (CO) only, <sup>d</sup> over 24 h period from 0500 h of one day to 0430 h the next day June - September; value of JS reported given by Van Herk et al. (2011) for Ewers et al. (2005).
Figure 1. (a) Land cover classes at the study area (Chasmer et al., 2014). The approximate locations and number of sap flow sensors are denoted by tree symbols of different sizes (note symbols appearing to be located in wetlands are the result of mapping limitations and are in fact located on plateaus). The locations of the landscape (ET_{LAND}) and wetland (ET_{BOG}) eddy covariance towers, with the solid and hatched shaded areas corresponding to the growing season flux footprint of the landscape and wetland towers respectively. The coloured cells illustrate the distribution of sapwood area (cm$^2$) derived from a 1 m resolution canopy height model and empirical allometric relationships resampled to 10 m resolution for figure’s clarity. (b) Spatial extent of peatlands occurring within the boreal zone extracted from the Peatlands of Canada database (Tarnocai et al., 2005) and consisting of landscapes characterized by permafrost-free channel fens, bogs and black spruce forested permafrost peat plateaus as described by (Zoltai and Tarnocai, 1975), and the location of the Scotty Creek Research Station (ScCr).

215x166mm (300 x 300 DPI)
Figure 2. Allometric relationships between (a) tree height (m) and diameter at breast height (cm) based on 198 trees measured within the landscape eddy covariance footprint at Scotty Creek in 2012, 2015, and 2016 and (b) diameter at breast height (cm) and sapwood area (cm²) based on 47 trees measured within the landscape eddy covariance footprint at Scotty Creek in 2016.

245x409mm (300 x 300 DPI)
Figure 3. (a) Daily total precipitation at Scotty Creek over the 2013 study period. (b) Average ($n = 22$) $J_S$ (black), and the minimum and maximum flux (grey). (c) Evapotranspiration of the forest-wetland landscape ($ET_{LAND}$), (d) vapour pressure deficit (VPD), (e) photosynthetically active radiation (PAR) and (f) 2 m air temperature recorded at the landscape eddy covariance tower over the study period.
Figure 4. (a) Evapotranspiration (ET) for different landcover types, namely landscape (LAND), forest (FOR) and wetlands (BOG) for 2013 based on data from the landscape eddy covariance tower. Vertical lines correspond to ± one standard deviation. (b) Upscaled landscape, forest and wetland transpiration ($T_{BS}$) using tree level sap flux density measurements. Vertical lines correspond ± one standard deviation on the Monte Carlo uncertainty analysis. (c) The contribution of black spruce transpiration to evapotranspiration ($T_{BS}/ET \times 100\%$) for the different landcover types (e.g. landscape, forest, wetland) in 2013. Points represent the upper limit of $T_{BS}$ assuming trees ≤5.4 cm at breast height are entirely composed of conducting tissue and trees >5.4 cm at breast height have a sapwood area equal to half the cross sectional area.
Figure S1. Relationship between landscape (ET\textsubscript{LAND}) and wetland (ET\textsubscript{BOG}) half-hourly water flux measured at Scotty Creek in (a) 2014, (b) 2015 and (c) 2016. The mean slope and intercept for the three-year period was used to calculate ET\textsubscript{BOG} in 2013 when it was not measured.
**Figure S1.** (a) Daily total landscape water flux (ET\textsubscript{LAND}) measured at the landscape eddy covariance tower at Scotty Creek during the 2013 study period. (b) Daily total forest (i.e., plateau) water flux (ET\textsubscript{FOR}) derived as the residual from ET\textsubscript{LAND} and the wetland water flux (ET\textsubscript{BOG}). Error bars refer to the confidence intervals of the derived residuals. (c) Daily total ET\textsubscript{BOG} derived from the mean slope and intercept of the relationship between ET\textsubscript{LAND} and ET\textsubscript{BOG} 2014 – 2016 at Scotty Creek. Error bars refer to the confidence interval of the derived estimates.
Figure S3: Probability density of the residuals resulting from the power function defining the relationship between (a) tree height and diameter at breast height and, (b) diameter at breast height and sapwood area at Scotty Creek. The residuals conform to a normal distribution.
Figure S4. Distribution of tree height (m) within the landscape eddy covariance footprint at Scotty Creek, extracted from the CHM. Average tree height was determined to be 2.2 m +/- 1.2 (shown in red; minimum = 1.0 m, maximum = 12.6 m), and was not measured for the instrumented trees.
Figure S5. Distribution of DBH (cm) within the landscape eddy covariance footprint at Scotty Creek, estimated allometrically from the relationship between the measured trees and CHM. Average DBH was determined to be $2.7\text{ cm} \pm 1.4$ (shown in red; minimum = $1.2\text{ cm}$, maximum = $15.1\text{ cm}$), in contrast to $10.6\text{ cm} \pm 0.5$ for the instrumented trees.
Figure S6. Distribution of sapwood area (cm$^2$) within the landscape eddy covariance footprint at Scotty Creek, estimated allometrically from the relationship between the measured trees and CHM. Average sapwood area was determined to be 1.8 cm$^2$ +/- 2.0 (shown in red; minimum = 0.4 cm$^2$, maximum = 37.1 cm$^2$), and was not measured for the instrumented trees.