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Assessing the environmental controls on Scots pine transpiration and the implications for water partitioning in a boreal headwater catchment

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ABSTRACT

Climate change projections indicate reduced summer precipitation and increased air temperature for the northern high latitudes. These climate changes are likely to alter forest water budgets of which plant transpiration (*T*) forms a significant component. Plant transpiration is regulated by stomata behavior of particular species, which is constrained by ambient air and soil conditions. Here, we measured sap flow in a Scots pine (*Pinus Sylvestris*) plantation in a low energy Scottish headwater catchment during the main summer growth period. Effects of rainfall on forest transpiration, as well as the response of *T* to four environmental variables were investigated at a daily scale. In this boreal environment, transpiration was mainly restricted by radiation and vapor pressure deficit. Air temperature was the least important controlling factor. Soil water became an important factor when rainfall was limited. Frequent but small rain events dictated that precipitation met short-term transpiration demand most of the time. The trees needed supplementary water from antecedent soil water stores when weekly rainfall was below ~8 mm, but such periods were rare. Water exchange mainly occurred in the canopy or upper 10 cm of the soil, with 47% of rainfall transpired, 45% intercepted and < 8% evaporated from the soil surface. Understanding interactions between forests and their hydroclimate, as well as the role of forests in water partitioning is crucial to assist a sustainable land and water management in a changing climate. Whilst such studies are common in semi-arid regions, they are limited in boreal zones, therefore, our findings are a valuable contribution to understanding plant-water relations in a changing environment.

1. Introduction

Plant transpiration (*T*) plays an important role in forest water budgets, as it affects the water partitioning in soils, aquifers and streams (Le Maitre et al., 1999; Vivoni et al., 2008; Deutscher et al., 2016). Precipitation has increased in the Northern Hemisphere over the last two to three decades (Easterling et al., 2000; Dore, 2005; IPCC, 2013) which can impact northern ecosystem composition and productivity (Lindner et al., 2008; Ruckstuhl et al., 2008; Chertov et al., 2010). While annual precipitation is predicted to further increase in the future (IPCC, 2013; Krasting et al., 2013), summer rain is projected to decrease in many northern areas possibly falling in fewer higher intensity events (Lindner et al., 2008; IPCC, 2013). In such circumstances, plants may face severe challenges to maintain productivity with foreseeable more frequent occurrence of water stress strongly associated with the precipitation and soil moisture dynamics (Porporato et al., 2001; Lisar et al., 2012). Therefore, a comprehensive understanding of the precipitation effects and soil water controls on plant water use is necessary and holds the key to adapting water and land use management to the future climate change.

T is regulated by stomata behavior constrained by both atmospheric conditions and soil water availability (Whitehead, 1998; Buckley et al., 2003; Wang et al., 2014). The mechanisms have been extensively explored at multiple scales from stomata and leaf to whole tree and ecosystem levels (Jarvis and McNaughton, 1986; Schulze et al., 1994; Bovard et al., 2005). Among the constraining variables, atmospheric vapor pressure deficit (*VPD*) and solar radiation (*Rs*) are the two major dominant controlling factors (Bovard et al., 2005). However, secondary controlling factors (such as temperature, *Ta*, soil water content, *θ*) vary with climates and species (Guo et al., 2010; Chen et al., 2014). In addition, rainfall can also affect *T* by altering atmospheric demand (or potential evapotranspiration, *ETp*) and soil water content (Findell and Eltahir, 1997). For example, rainless days usually create more favorable conditions for transpiration (higher *Rs* and *VPD*) than rainy days. In arid/semi-arid areas, where vegetation growth is usually water-limited, plant water use highly relies on rainwater, and rainfall pulses stimulate *T* after a certain rainfall threshold is reached, because increased water storage in the root zone increases soil water availability (Ogle and

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Reynolds, 2004; Potts et al., 2006; Raz-Yaseef et al., 2012).

In contrast to semi-arid regions, in the low-energy northern high latitudes (> 45°N) vegetation growth is usually limited by radiation and not water availability. The studies in this region put a stronger focus on climate-driven vegetation greening attributed mainly to warming temperatures (Buitenwerf et al., 2015; Garonna et al., 2016). Precipitation, soil moisture, and snow accumulation and melt also contribute to enhanced vegetation growth (Luus et al., 2013), and this contribution can be highly variable in space and time (Barichivich et al., 2014). As the treeline has progressed poleward (Beringer et al., 2005; Pearson et al., 2013), investigations of tree water use and environmental controls are important for understanding ecosystem response to climate change, but such work in this critical region has so far been limited. Several studies have shown that tree water use in the high latitudes is often closely linked to permafrost thaw since soil water from thawed permafrost can be comparable to soil water from summer rains (Kropp et al., 2017). Light intensity and humidity also closely restrict tree water use and productivity (Arneth et al., 1996; Gao et al., 2016; Zha et al., 2013). There is a lack of understanding on direct rainfall effects.

The natural vegetation over much of the Scottish Highlands would have been forest dominated by Scots pine (*Pinus sylvestris*), but a long history of clearance, burning and overgrazing by deer and sheep resulted in limited forest cover across Scotland. With the presence of frequent rainfall, low radiation and high humidity, plants are usually not under water stress during most of the year (Haria and Price, 2000). However, future projections of decreased rainfall and increased intensity during growing seasons (Gosling, 2012; Capell et al., 2013) may result in a decreased water availability, increasing the probability that vegetation would suffer from more frequent and prolonged water stress (Zhang et al., 2008; Trahan and Schubert, 2016). The role of soil water in regulating plant transpiration may become more important (Geris et al., 2015b) but it is not yet fully understood; neither is the role of plant transpiration on canopy water partitioning relative to interception and soil evaporation losses. Therefore, in this study, we measured sap flow in a Scots pine plantation in a Scottish headwater catchment, aiming to: (1) investigate the dynamics of transpiration in Scots pine in this low energy boreal environment in the summer season which may be more water-limited than other seasons; (2) examine the interactive environmental controls on transpiration; and (3) understand the implications for water partitioning in the forest in terms of likely effects of future climatic conditions.

2. Materials and methods

2.1. Study site

This study was conducted in the Bruntland Burn catchment (3.2 km^2, 57.04°N, 3.13°W) in the Scottish Highlands (Fig. 1). It is described in detail elsewhere (Birkel et al., 2011; Tetzlaff et al., 2014; Soulsby et al., 2015; Blumstock et al., 2016). The climate is boreal oceanic; the recent decadal mean annual maximum temperature is 19.4 ± 1.3 °C in July, and mean annual minimum temperature is −1.0 ± 1.6 °C in January. Mean annual precipitation (*P*) is around 1000 mm; it is relatively evenly distributed but lowest (mean ~65 mm/month) in April-July and highest (~105 mm/month) in October-February. Throughout the year, it most commonly falls as low-intensity rain; snow is generally < 5% of annual *P* and tends to lie for short periods (a few days to a few weeks) in January and February and melts quickly. Annual potential evapotranspiration (*ETp*) calculated using the Penman-Monteith method (Allen et al., 1998) is around 400 mm and annual runoff at the catchment outlet is around 700 mm (Soulsby et al., 2015).

The geology of the catchment is mainly granite and associated metamorphic rocks (Tetzlaff et al., 2014; Dick et al., 2015). Elevation ranges from around 250 m.a.s.l at the flat valley bottom, to about 550 m on the steeper slopes (Fig. 1). Organic-rich soils dominate the catchment, with large areas of deep (> 1 m) peats in valley bottoms and shallow (< 0.5 m) peats on the lower hillslopes. The steeper slopes with the studied plantation are characterized by podzols which have a 0.1–0.2 m deep O horizon overlying a freely draining mineral sub-soil.

The dominant vegetation in the catchment is heather (*Calluna vulgaris* and *Erica tetralix*) shrubs with a canopy height 0.3–0.6 m, distributed throughout the valley and hillslopes. Trees, mostly Scots pine, cover about 10% of the catchment, mainly in plantations near the outlet and as natural forest on the south-facing steeper slopes. The tree height ranges from 5 m in the natural forest to 15 m in the plantation. The understory is sparsely vegetated in the plantation where canopies are dense and light penetration is low. The majority of tree roots are present in the upper 0.3 m of the soils (Geris et al., 2015a) but extend a few meters horizontally. Trees are ~30 years old without any cutting/thinning history. Tree density is lower in the middle part of the plantation (960 trees/ha) than the upper and lower parts (> 2000 trees/ha).

2.2. Measurements

This study covers July to September 2015, a period in the year that is usually the warmest and driest. In total, 32 sets of Granier-type (Granier, 1987) thermal dissipation sap flow probes (TDP probes, *Dynamax Inc. Huston,* USA) were installed on 10 trees at 1.3 m high above ground with a range of stem sizes (10–32 cm in diameter at breast height, *DBH*). Each set of sensors comprises 1 heater probe and 1 thermocouple probe 4 cm below it. Four sensors were installed on trees with *DBH* over 20 cm in four cardinal directions; two or three sensors on trees with *DBH* of 15–20 cm on the south-north (and west when applying) sides; and one sensor on 1 tree with *DBH* below 15 cm. Data were collected using a CR1000 data logger (*Campbell Scientific*, USA) at an hourly interval. Incremental wood cores were taken from 51 trees in 3 plots in the plantation at the end of study period to establish the relationship between sapwood area (*As*) and *DBH* at 1.3 m above ground ($As = 0.0049 \times DBH^{2.0048}$, $R^2 = 0.95$). The average ratio of sapwood area to forest area (25 m^2/ha) obtained from surveys in the three plots was used to estimate forest transpiration.

An automatic weather station (*Environmental Measurement Limited, North Shields, UK*) was established near the forest site in an open area (Fig. 1), giving continuous measurements of air temperature (*Ta*), relative humidity (*RH*), net radiation (*Rn*), soil heat flux (*G*), precipitation (*P*), wind speed/direction, and atmospheric pressure. Volumetric soil water content (θ) was measured near the sample trees using time domain reflectometry (TDR) soil moisture probes (model CS616, *Campbell Scientific, Inc. USA*). Sensors were calibrated against gravimetric soil water content and bulk density in the lab with a range of water content. Two replicate TDR probes were inserted at depths of 0.1, 0.2 and 0.4 m prior to the sap flow measurements commencing, allowing soil stabilization after refilling of the pits. The slopes derived from a 1 m resolution LiDAR elevation map (Fig. 1) show that most of the plantation is relatively flat. Measurement of soil moisture at one location will not capture the spatial heterogeneity within the plantation, but comparison to measurements elsewhere in the catchment showed that the sensors at this site captured the general soil water dynamics in response to rainfall and evapotranspiration. Meteorological parameters and soil water content measurements were recorded by CR800 data loggers (*Campbell Scientific, Inc. USA*) at 15-min intervals.

2.3. Methods

Forest transpiration was estimated using the average sap flux density per unit sapwood area multiplied by the sapwood area index (Granier et al., 1996). Measurements of forest transpiration and hydroclimatic variables, including *Ta*, vapor pressure deficit (*VPD*, calculated from mean *Ta* and *RH*, Allen et al., 1998), *Rn* and θ, were

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